Engineer Research and Development Center

# Habitat Modeling and Assessment for the Missouri River Recovery Program

EWN for Water Operations

Strategic Meeting

March 31 – April 1 2015

Craig Fischenich, ERDC Environmental Lab

# Background/Context

Engineer Research and Development Center

# Background/Context

- 2000/2003 BiOp (plover, tern, pallid sturgeon)
- Missouri River Recovery Implementation Committee (MRRIC) and Independent Science Advisory Panel (ISAP)
  - Spring Pulse
  - Adaptive Management
  - Effects Analysis



# Background - MRRP

**Management Plan:** The scope of the effort is **focused on removing or precluding jeopardy status and contributing to the recovery** of the three species. Will identify preferred alternative to be implemented within an adaptive management framework, collaborate with stakeholders and **fulfill NEPA requirements**.

- Team: USACE, USFWS, Effects Analysis leads
- Timeline: began in 2013, concludes in August 2016
- Products: PEIS and AM plan; ROD

**Effects Analysis:** Provides a mechanism for **quantifying the effects of past, ongoing and future USACE actions** on the 3 listed species and evaluating the potential benefits of proposed management actions

- Teams: Three teams, including ERDC, USGS, PNNL, USACE, and USFWS staff
- Timeline: Began fall 2013, phase 1 complete spring 2015
- Products: EA Phase 1 draft reports in October 2014, final Phase 1 reports in spring/summer 2015

# Background - MRRP

ERDC
Engineer Research and Development Center

**<u>Objectives and Targets</u>:** process to define objectives and targets for birds and sturgeon management. Quantitative targets for birds are focused on plovers.

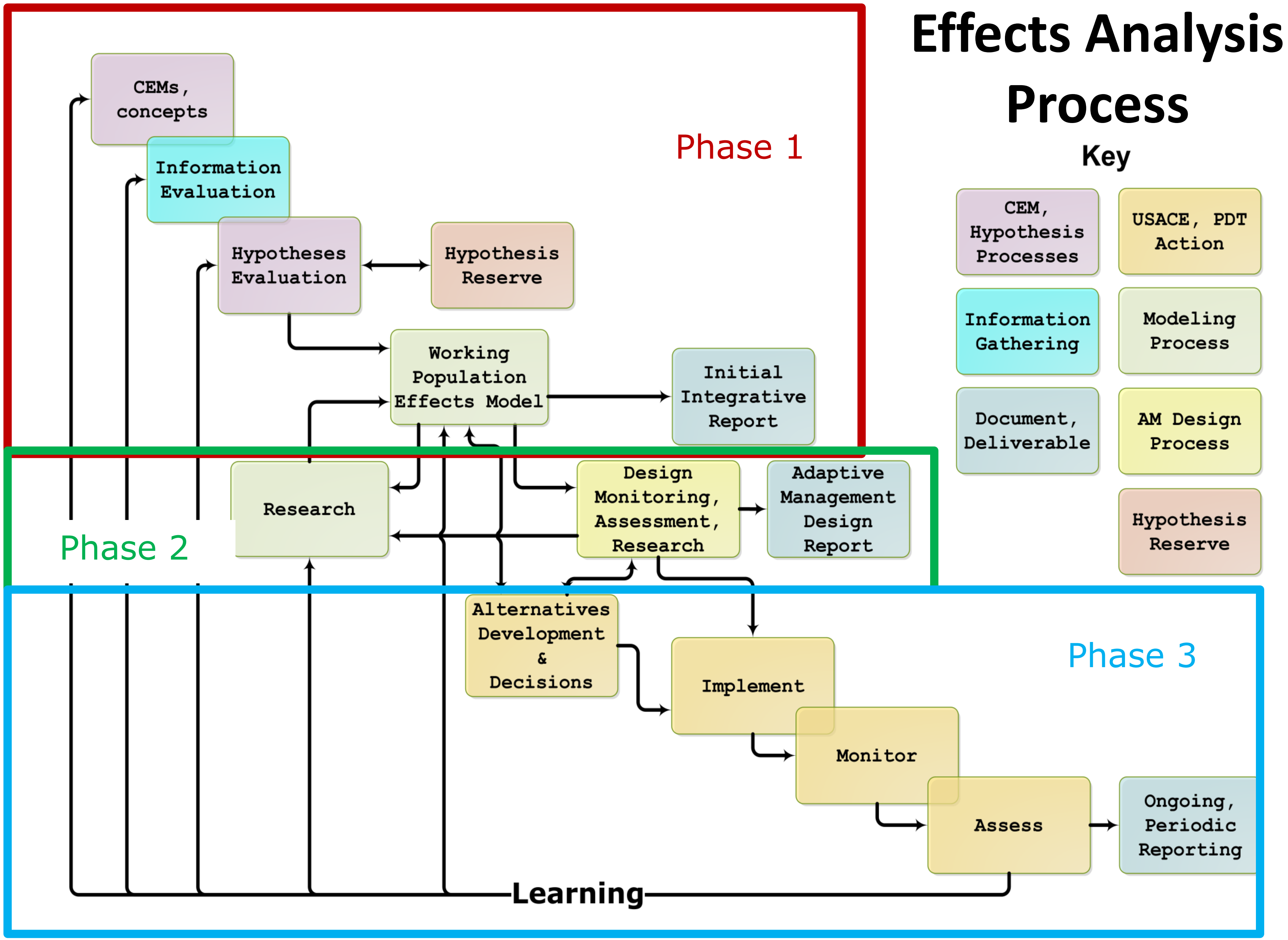
- Team: USFWS, assisted by EA leads and modelers
- Timeline: summer 2013 – spring 2015
- Products: Objectives (available), quantitative targets for plovers and criteria for sturgeon

**<u>Alternatives Development/PrOACT</u>:** process to define management alternatives (suites of actions) using a structured decision-making (PrOACT) approach with MRRIC to assess the effects of the management actions on species and a set of "human considerations" metrics reflecting stakeholder interests and trade-offs.

- Team: USACE, USFWS, EA leads
- Timeline: driven by MRRIC schedule: "test" alternatives (exploratory management actions) presented in February 2015, Round 1 alternatives in May 2015, Round 2 in August 2015, selection of preferred alternative to follow
- Product: Preferred alternative

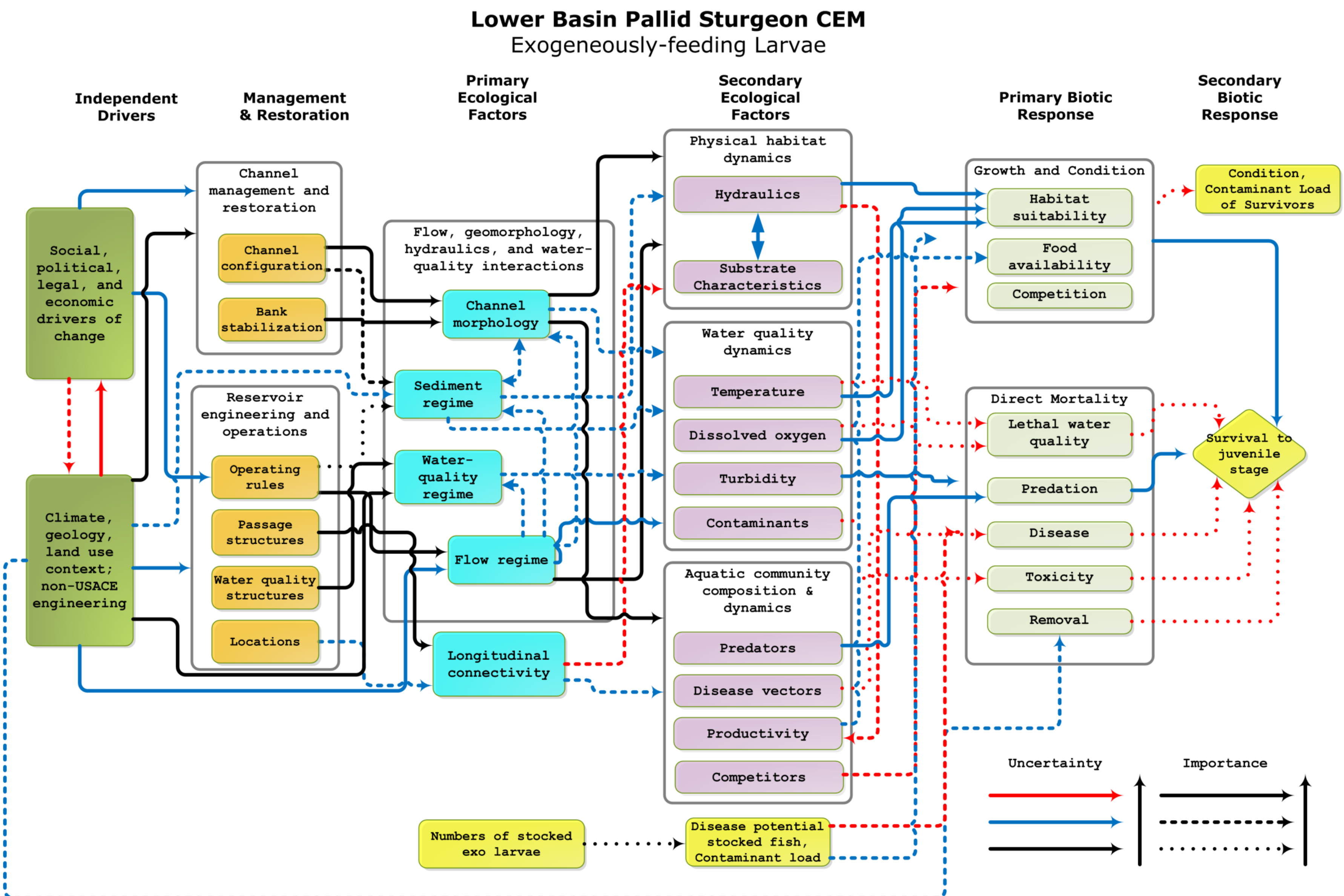
**<u>Adaptive Management Planning</u>:** Development of Adaptive Management Plan to accompany the PEIS that results from the Management Plan. Includes a research-focused "first increment" framework for pallid sturgeon management and a more traditional AM strategy for plovers and terns, as well as a governance and decision process that addresses both.

- Team: AM Process Team including staff from USACE, USFWS, PNNL, ERDC, Louis Berger
- Timeline: AM Governance structure and documentation in August 2014, began introducing pallid sturgeon framework in spring 2015, draft AM plan due October 2015
- Product: AM plan


Effects Analysis Process
Key
CEM, Hypothesis Processes
USACE, PDT Action
Information Gathering
Modeling Process
Document, Deliverable
AM Design Process
Hypothesis Reserve
Phase 1
CEMs, concepts
Information Evaluation
Hypotheses Evaluation
Hypothesis Reserve
Working Population Effects Model
Initial Integrative Report
Phase 2
Research
Design Monitoring, Assessment, Research
Adaptive Management Design Report
Phase 3
Alternatives Development & Decisions
Implement
Monitor
Assess
Ongoing, Periodic Reporting
Learning

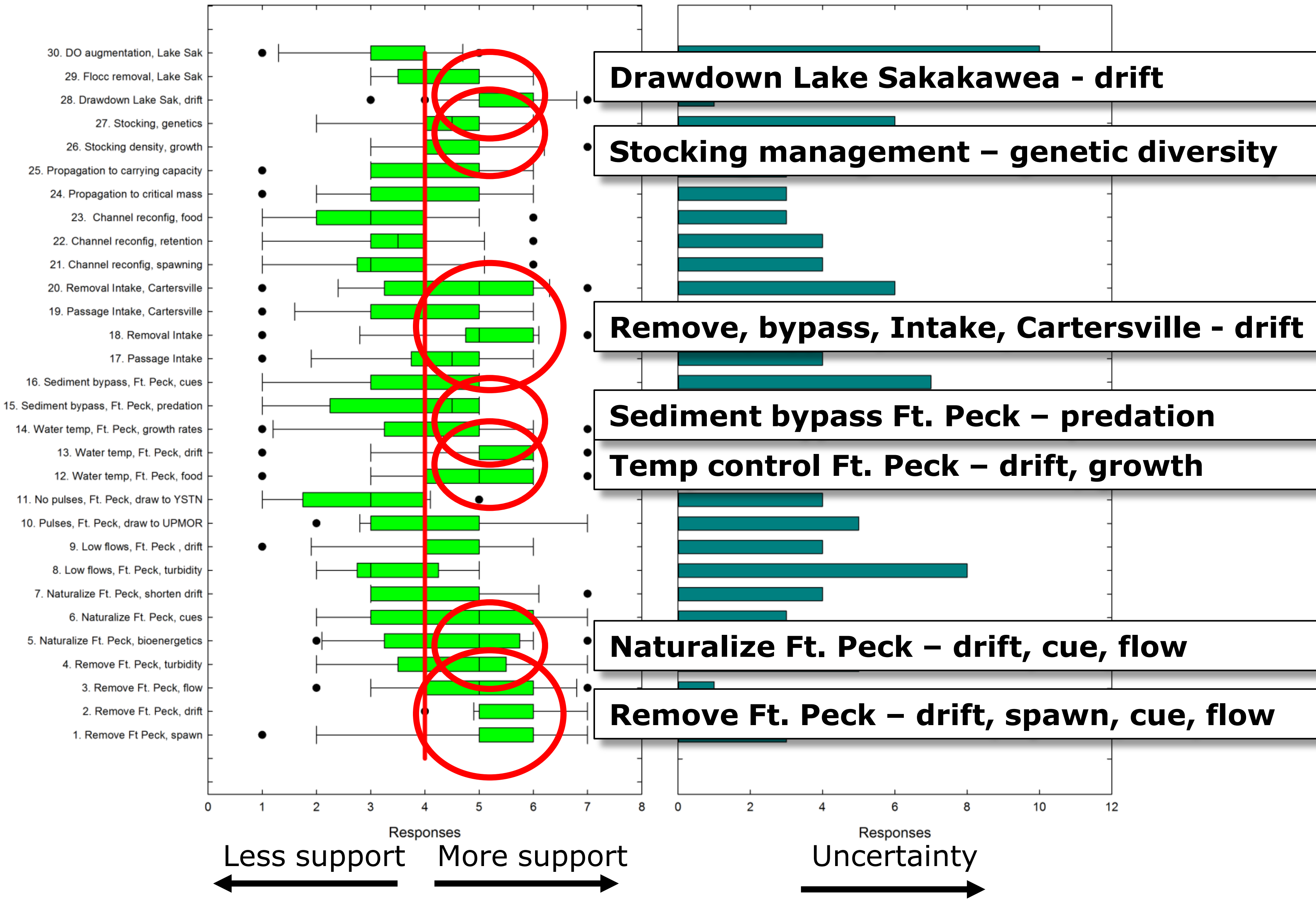
# Conceptual Models

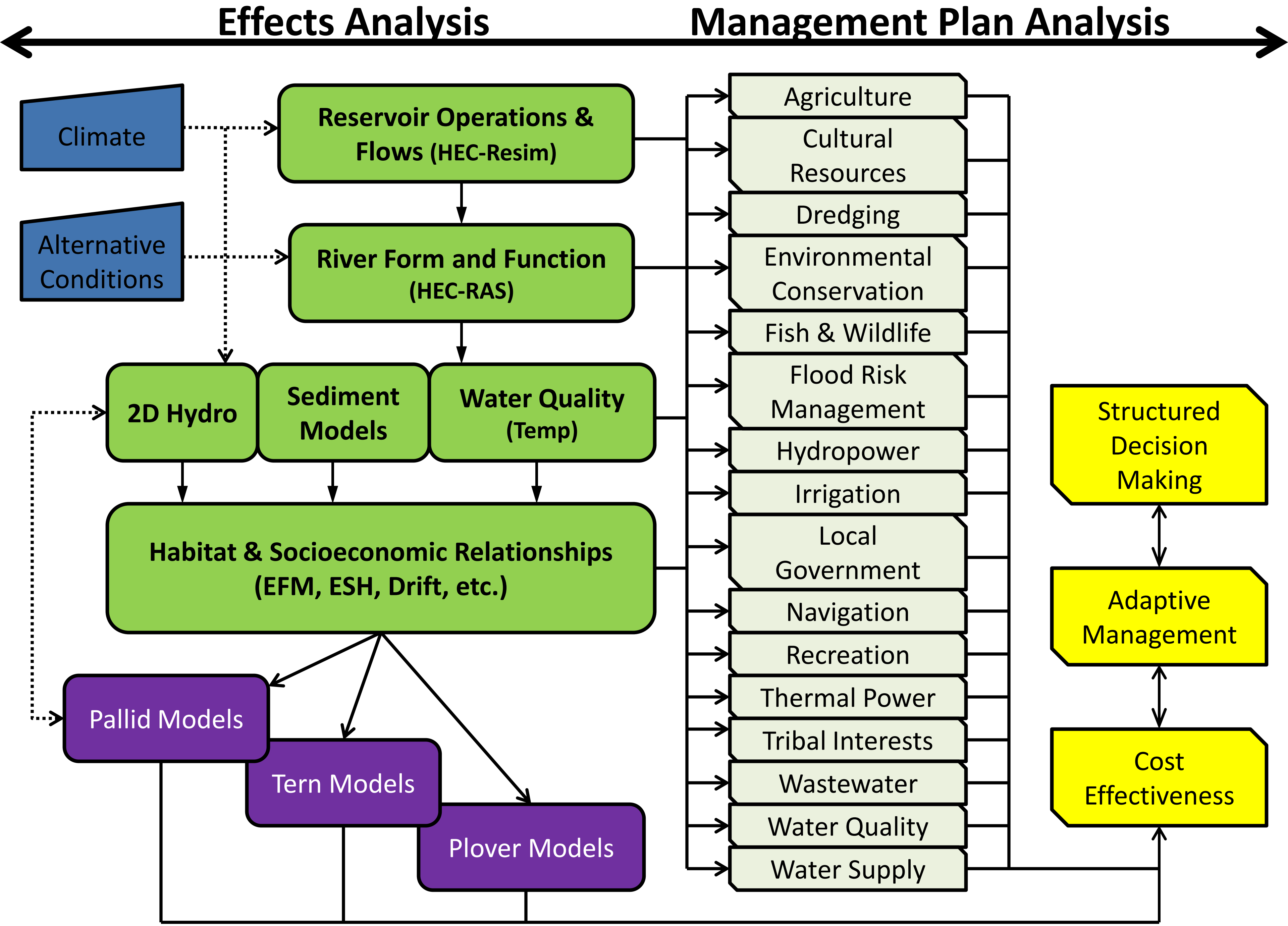
Engineer Research and Development Center




CEM provided by Robb Jacobson

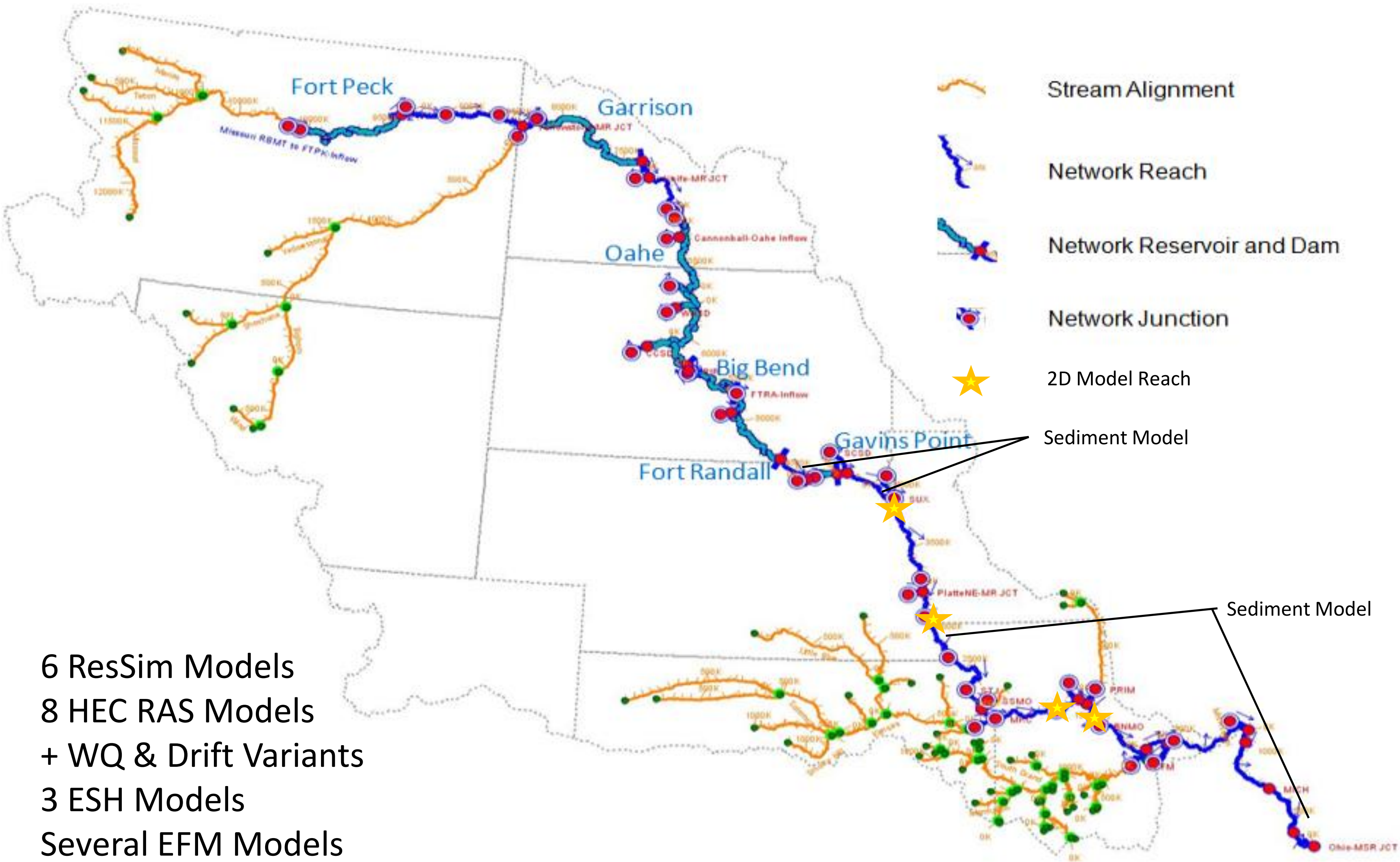
# Management Hypotheses Expert Survey




Effects Analysis
Management Plan Analysis
Climate
Alternative Conditions
Reservoir Operations & Flows (HEC-Resim)
River Form and Function (HEC-RAS)
2D Hydro
Sediment Models
Water Quality (Temp)
Habitat & Socioeconomic Relationships (EFM, ESH, Drift, etc.)
Pallid Models
Tern Models
Plover Models
Agriculture
Cultural Resources
Dredging
Environmental Conservation
Fish & Wildlife
Flood Risk Management
Hydropower
Irrigation
Local Government
Navigation
Recreation
Thermal Power
Tribal Interests
Wastewater
Water Quality
Water Supply
Structured Decision Making
Adaptive Management
Cost Effectiveness

# H&H Modeling

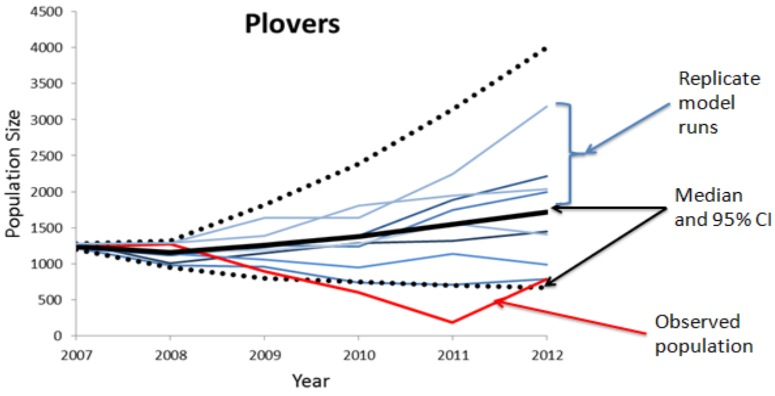
Engineer Research and Development Center

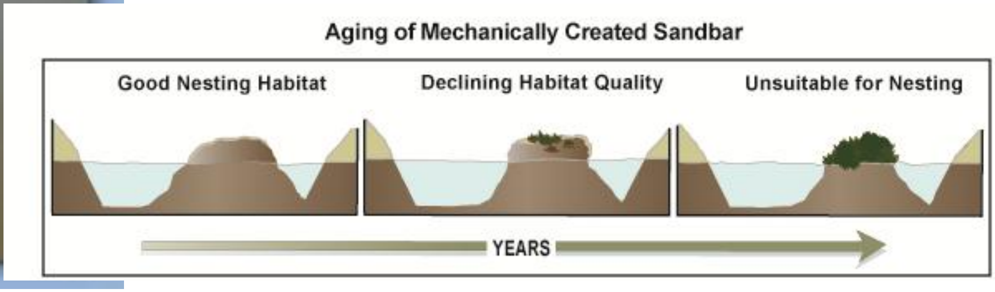



6 ResSim Models
8 HEC RAS Models
+ WQ & Drift Variants
3 ESH Models
Several EFM Models

# Plovers (and Terns) Emergent Sandbar Habitat

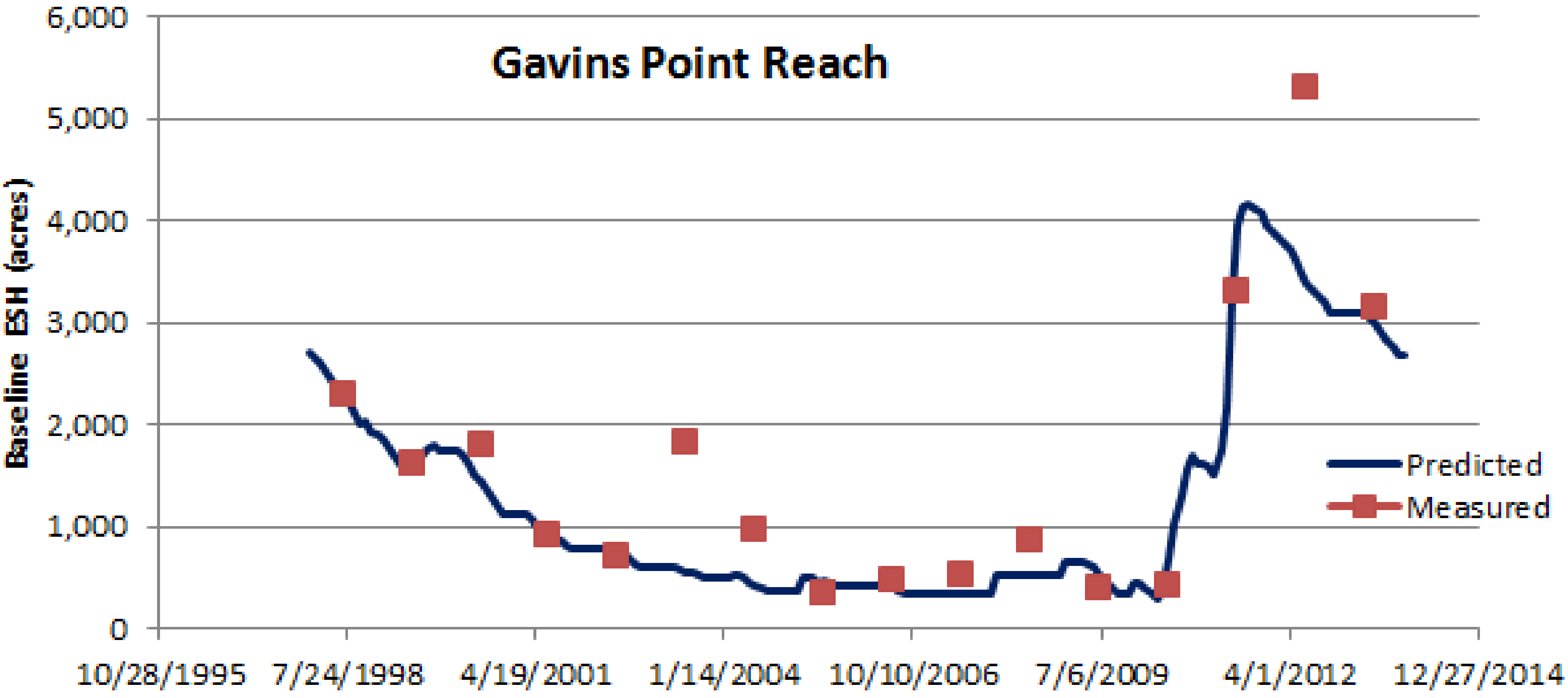
- Need for flow-dependent ESH relation
- Limited data & geomorphic modeling capability
- Previous model construct is sound but limited
  - Improved stage-area relations
  - loss rate function

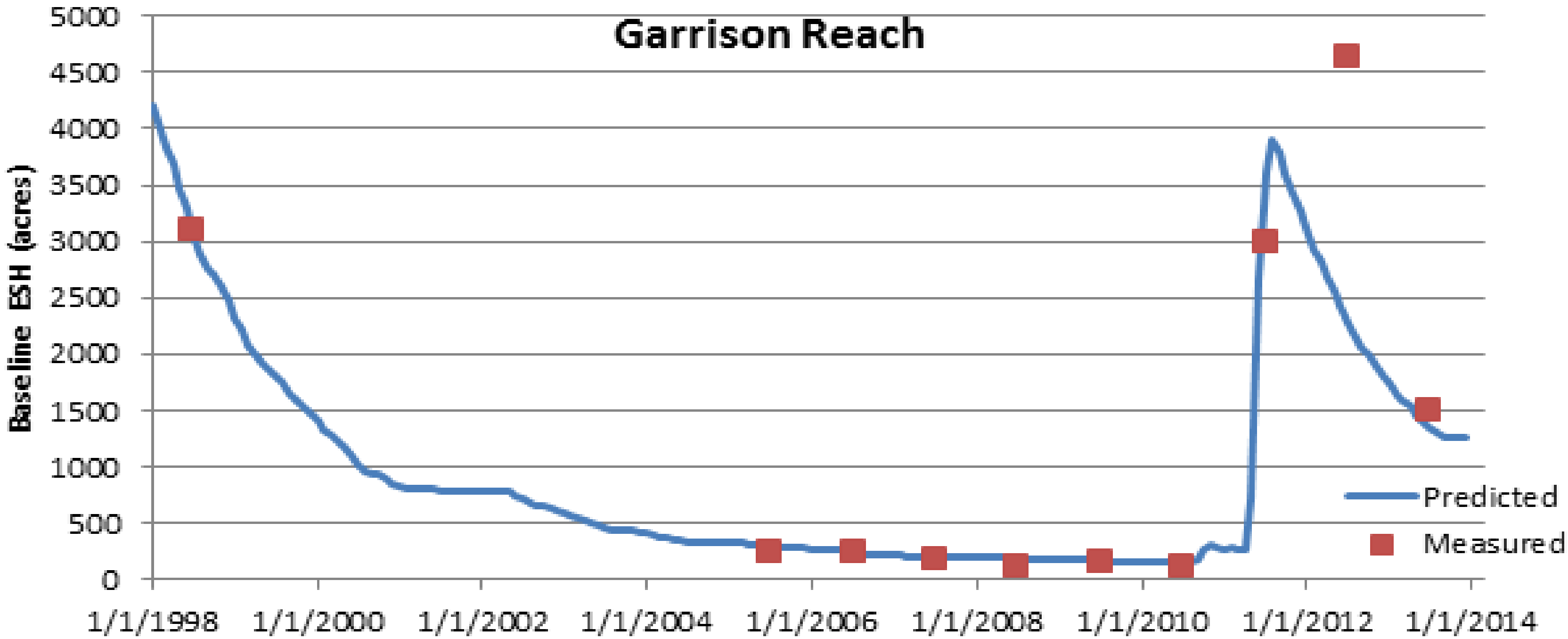


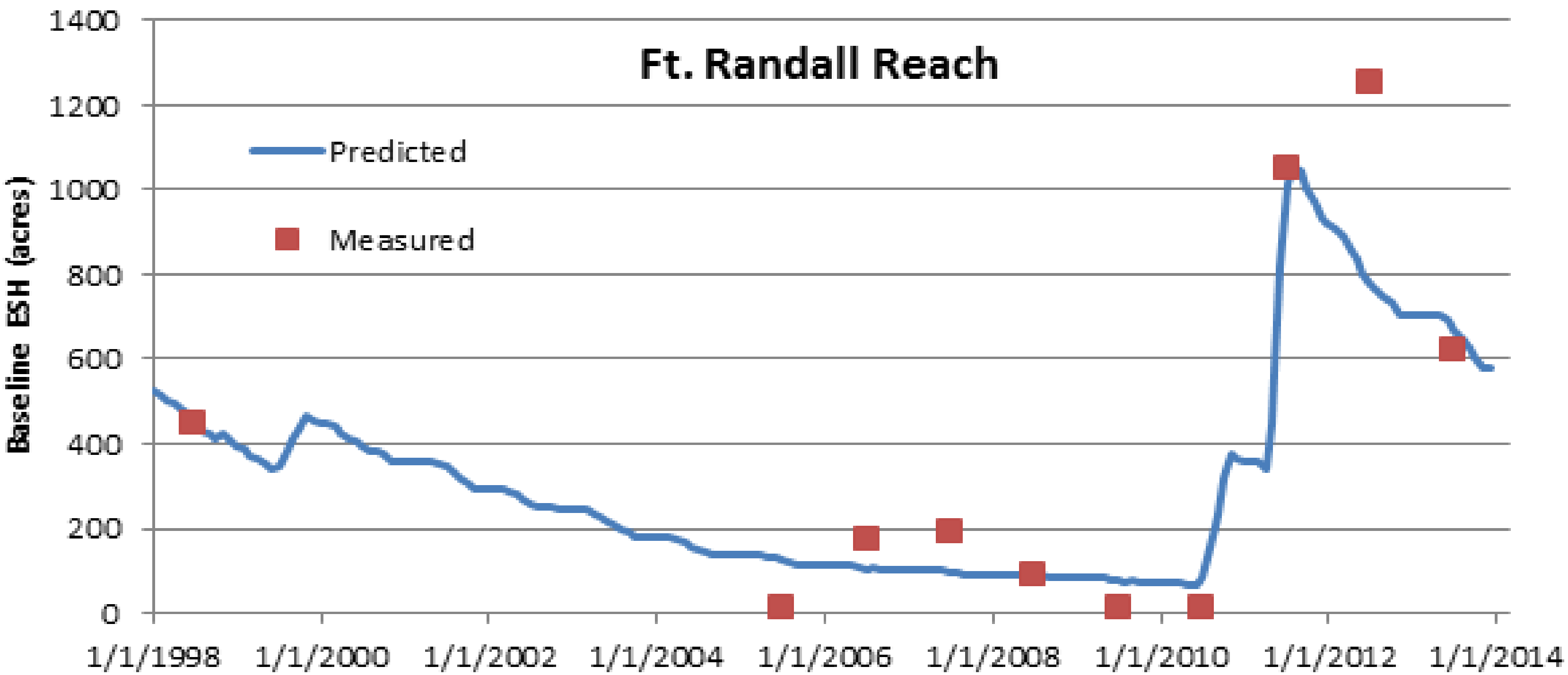



# ESH Model Performance

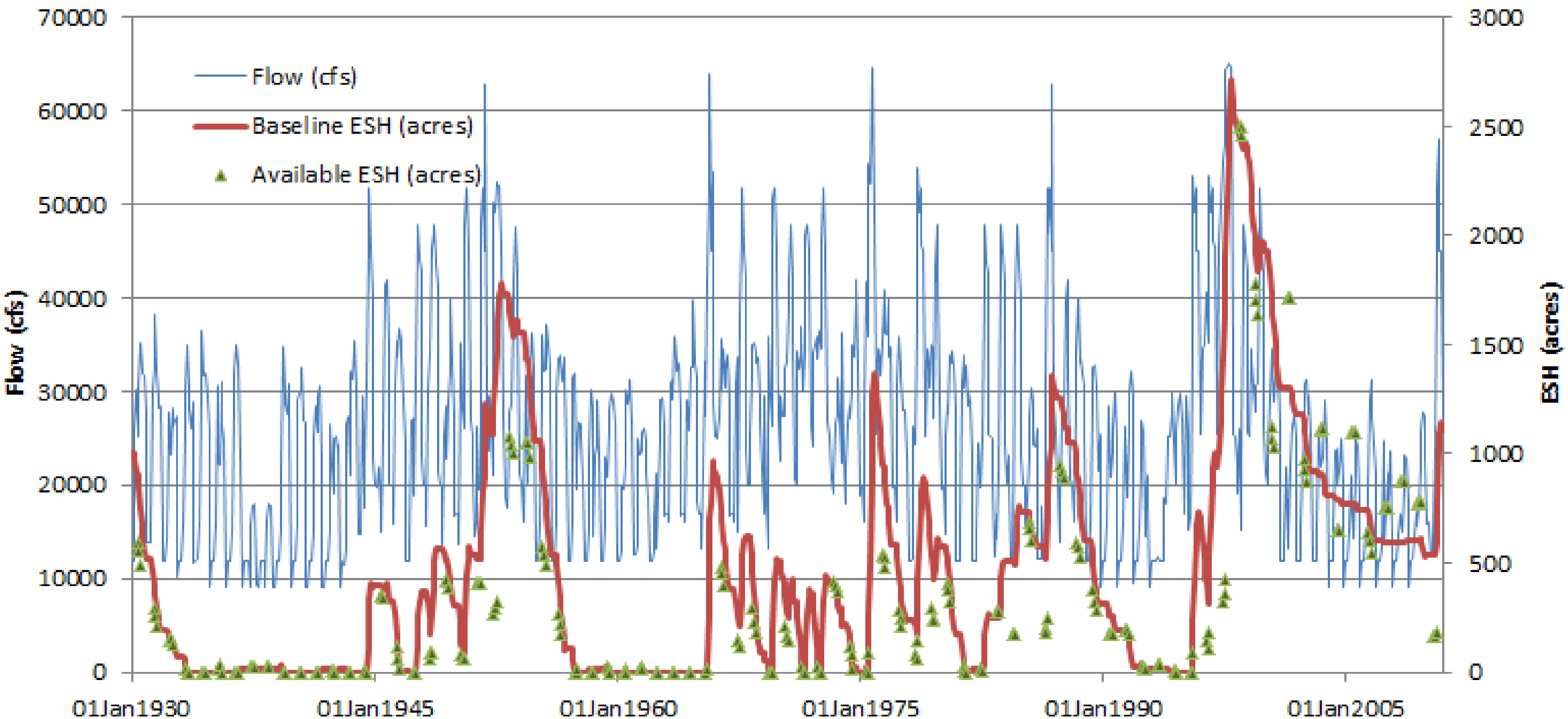
ERDC
Engineer Research and Development Center




Garrison Reach
Baseline ESH (acres)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1/1/1998
1/1/2000
1/1/2002
1/1/2004
1/1/2006
1/1/2008
1/1/2010
1/1/2012
1/1/2014
Predicted
Measured

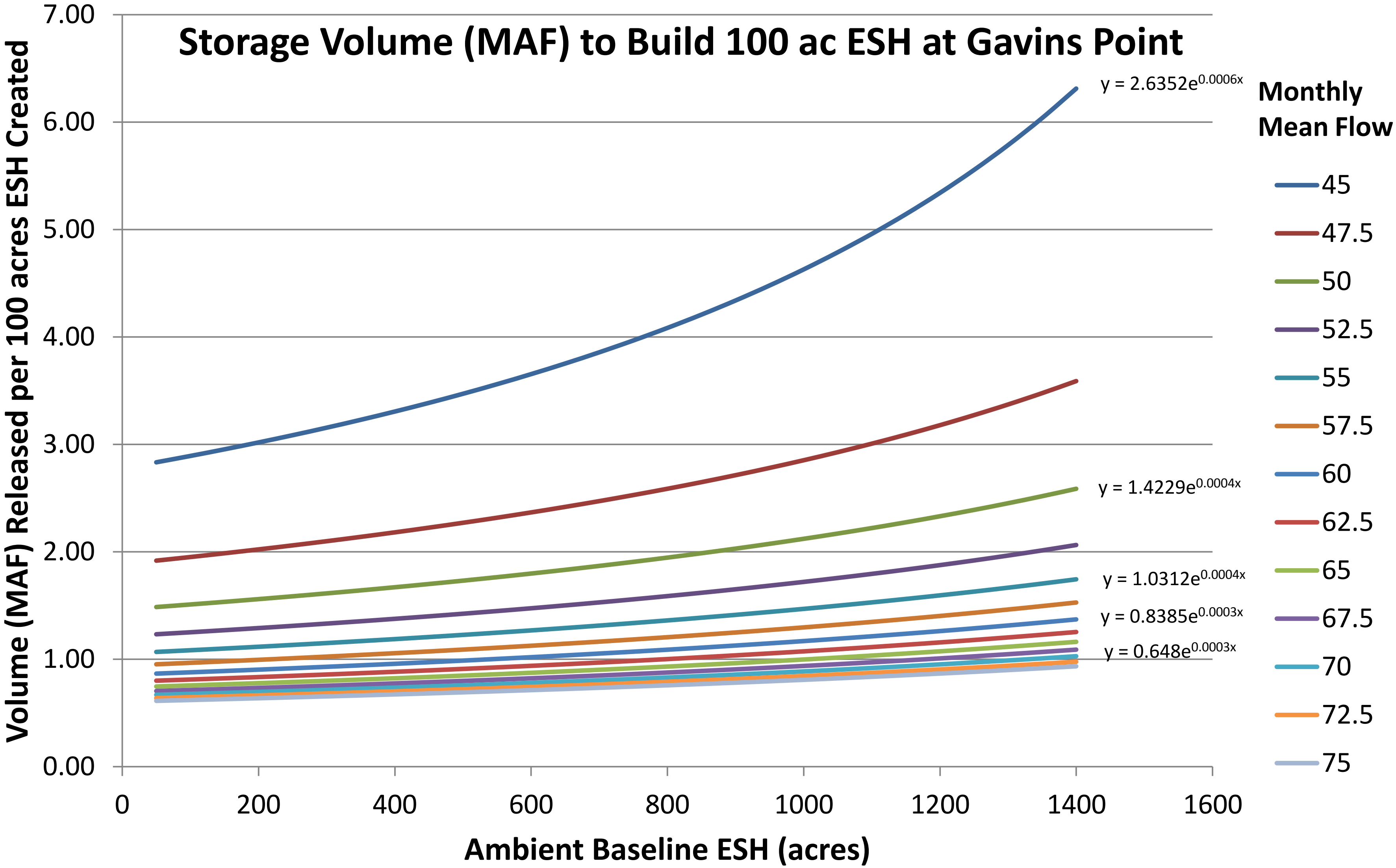

Ft. Randall Reach
Baseline ESH (acres)
1400
1200
1000
800
600
400
200
0
1/1/1998
1/1/2000
1/1/2002
1/1/2004
1/1/2006
1/1/2008
1/1/2010
1/1/2012
1/1/2014
Predicted
Measured

# Hindcast of ESH
# 1930 – 2010 Fully Regulated



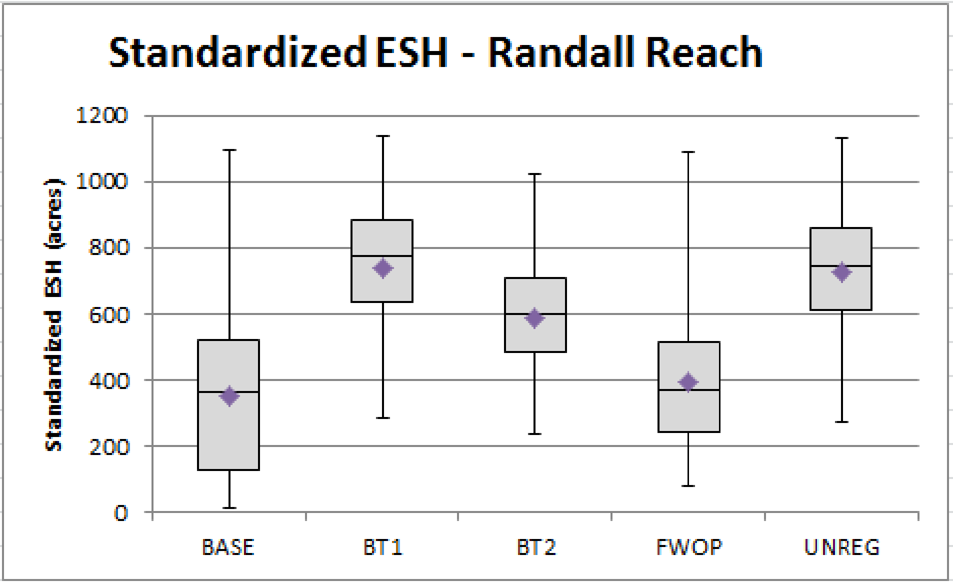
# Alternative Formulations

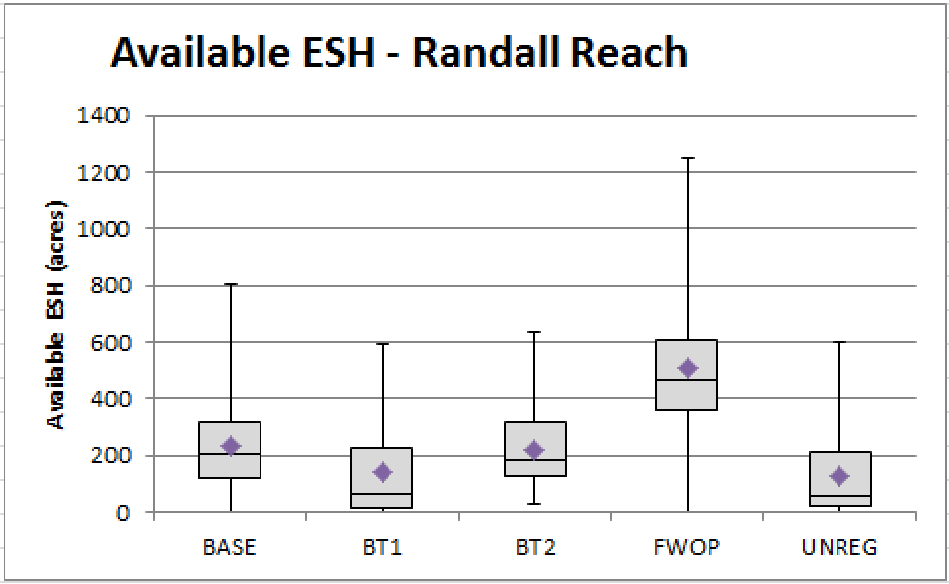
ERDC
Engineer Research and Development Center

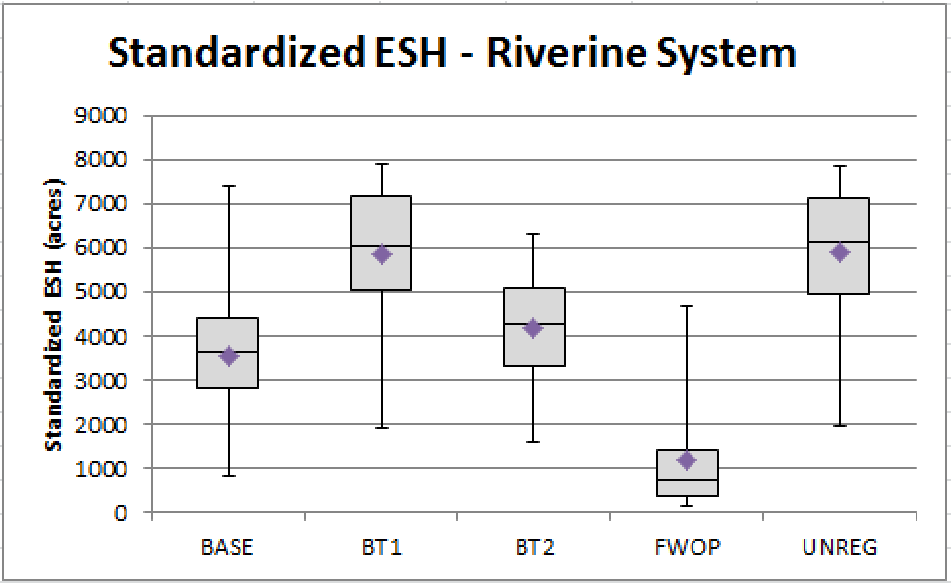


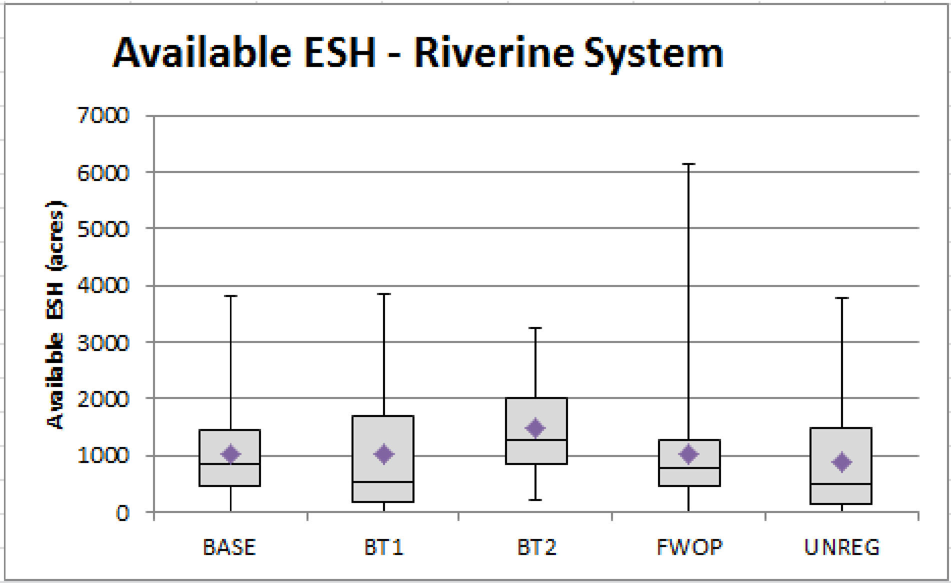
# Alternative Comparisons

ERDC
Engineer Research and Development Center



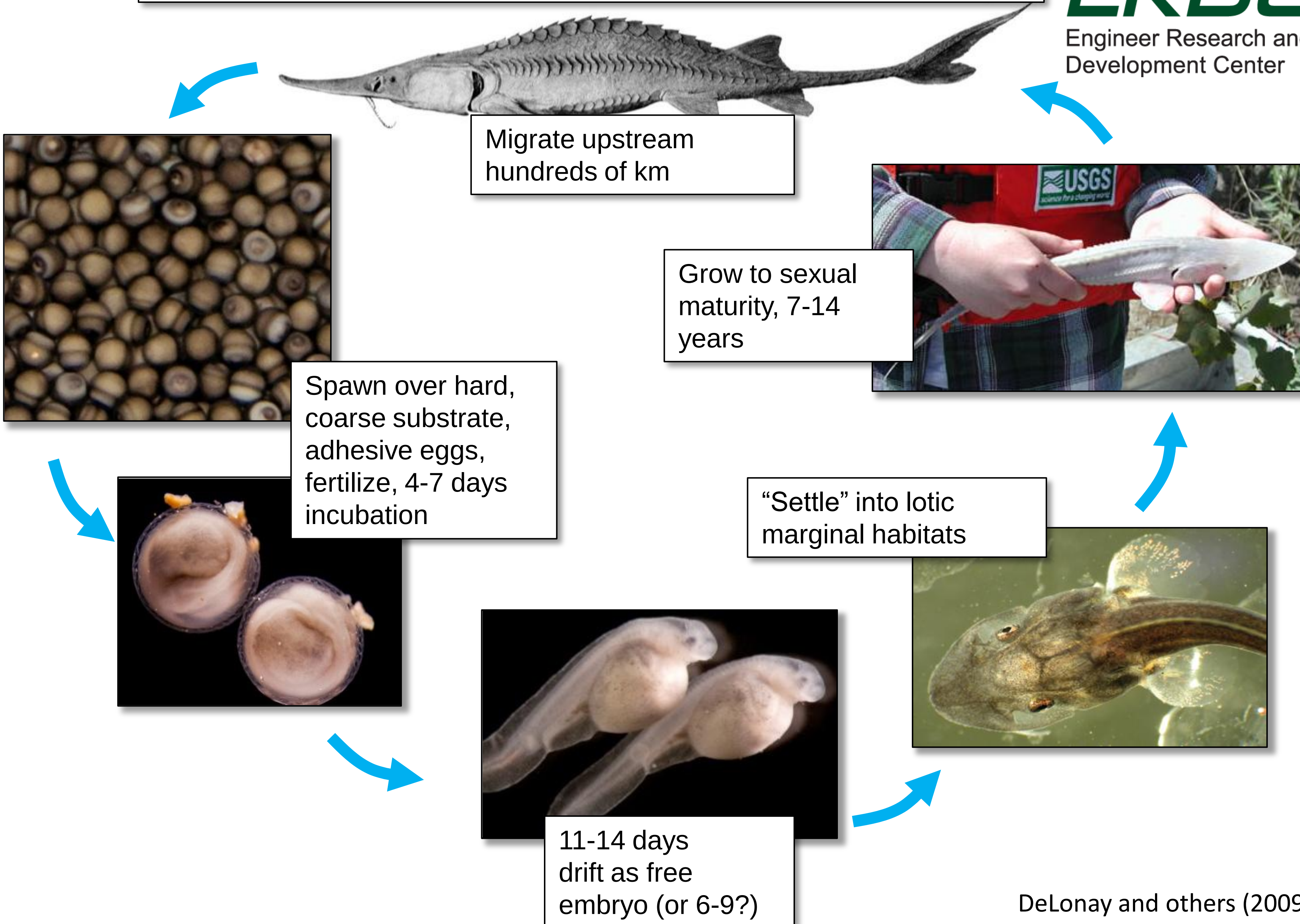



# Pallid Sturgeon (*Scaphirhynchus albus*)

ERDC
Engineer Research and Development Center



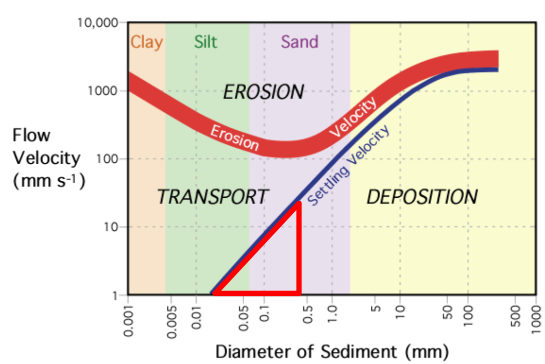

DeLonay and others (2009)

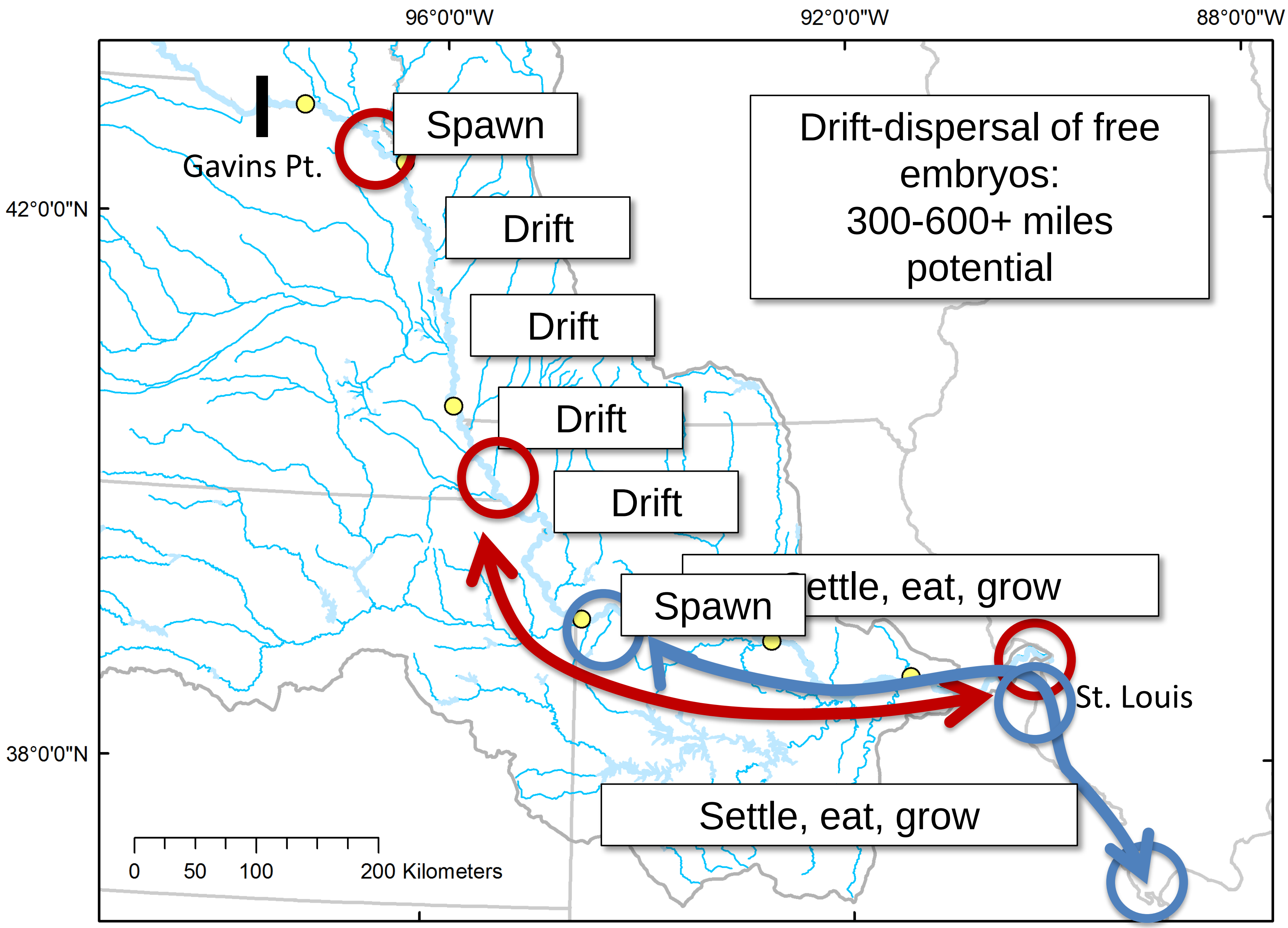
# Drift –Dispersal of Free Embryos

- 11-14 days to use up yolk sac
  - Temperature dependent
  - Interstitial residency: possibly - 5 days
- Adaptive behavior to drift, avoid predation
  - Probably not good to settle before transition
- At transition, need to feed immediately
  - Need food source – mostly chironomid larvae

**Uncertainties:**

- Immediate/delayed drift
- Ability to move
  - Really passive?
  - Lab observations vs field observations.
  - 90% within 1 m of bottom.
  - Drift at ~.9 * v
- Deleterious effects of turbulence?
- Importance of spawning substrate, interstitial space?





96°0'0"W
92°0'0"W
88°0'0"W
42°0'0"N
38°0'0"N
Gavins Pt.
Spawn
Drift
Drift
Drift
Drift
Drift-dispersal of free embryos:
300-600+ miles potential
Settle, eat, grow
Spawn
St. Louis
Settle, eat, grow
0 50 100 200 Kilometers

# Working Definitions: Functional Habitats

Engineer Research and Development Center

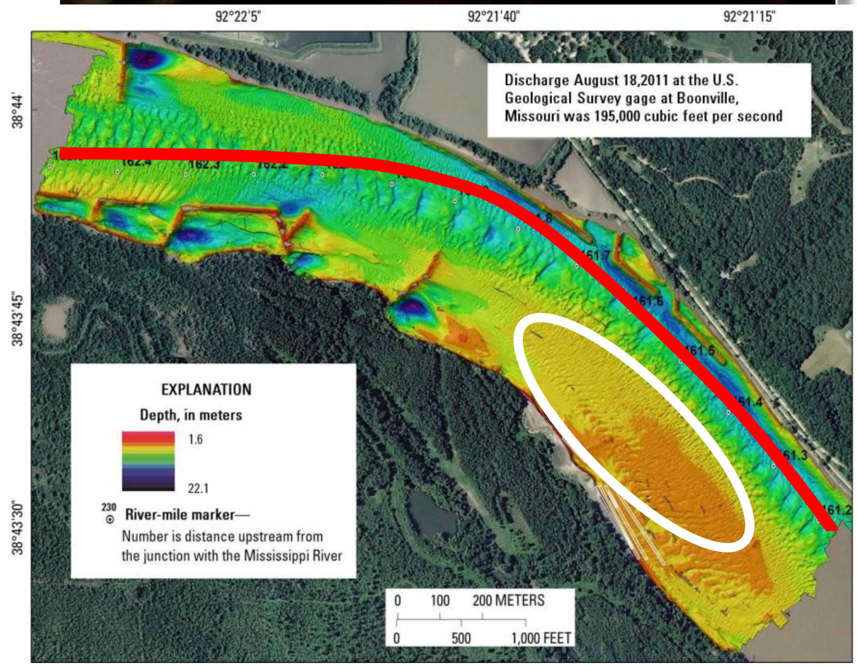
Hypotheses point to four functional habitat types that may be responsible for recruitment failure; limiting factors not yet identified:

- **Spawning habitat -** Convergent flow, high velocity, high turbulence, enhanced definitions based on Yellowstone reference.
- **Food habitats -** Stable, fine substrate especially for chironomid production for age-0 fish diet – depositional areas, velocities < 0.08 m/s
- **Foraging habitats -** Enough depth and velocity to provide access to drifting food, not too much, age-0 CPUE peaks at 1-3 m and 0.5 – 0.9 m/s (Ridenour and others, 2011)
- **Free embryo interception, retention -** Geometries that promote free-embryo transport from thalweg and retention

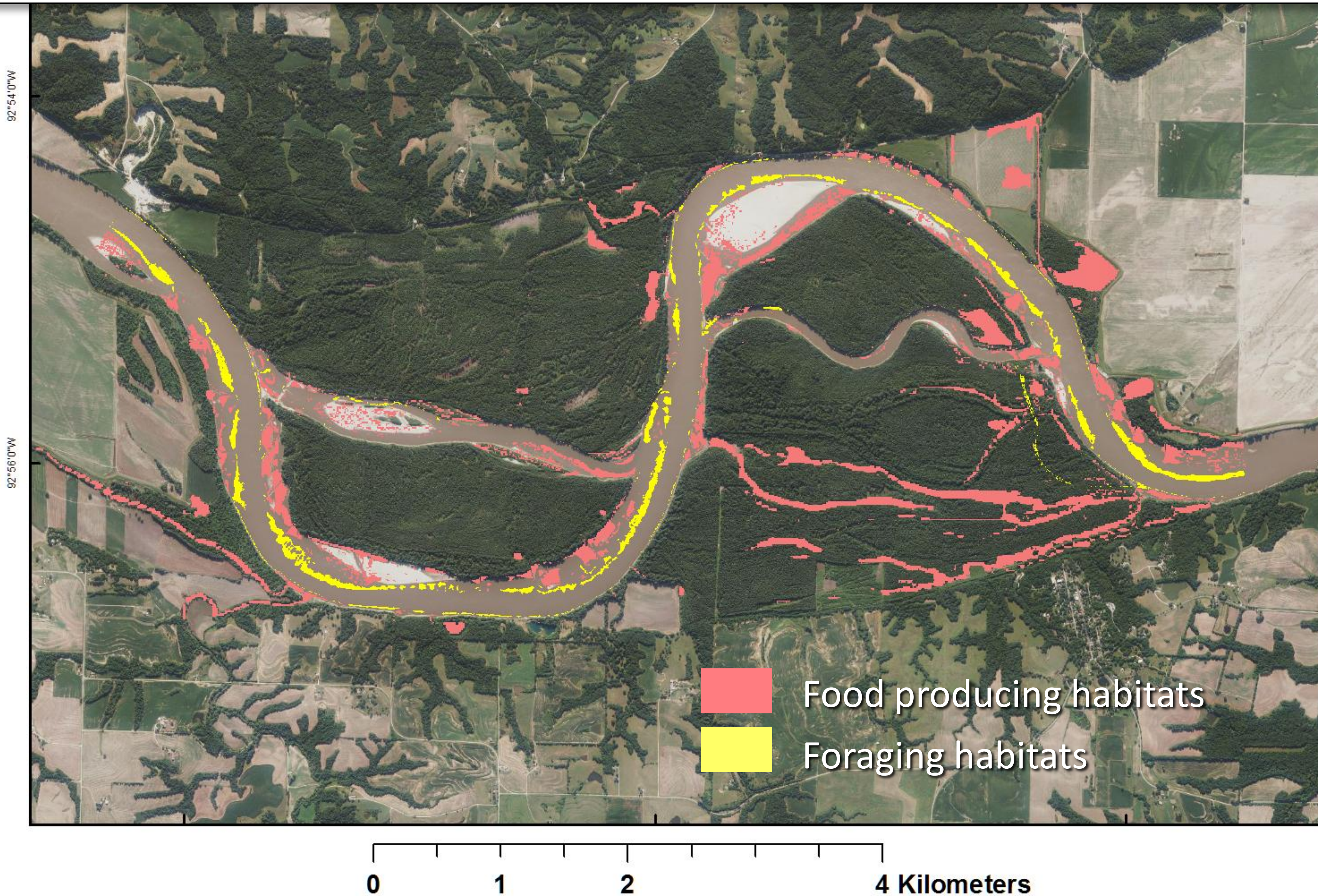
# Interception Rearing Complexes

ERDC
Engineer Research and
Development Center

- Provide needed habitat for free embryos through first winter (at least) – age0 – age1
- Located downstream from spawning sites
  - Spawning site minus typical drift distance
- Off-ramp hydraulics from navigation channel
- Food-producing and foraging habitat available, neither limiting.



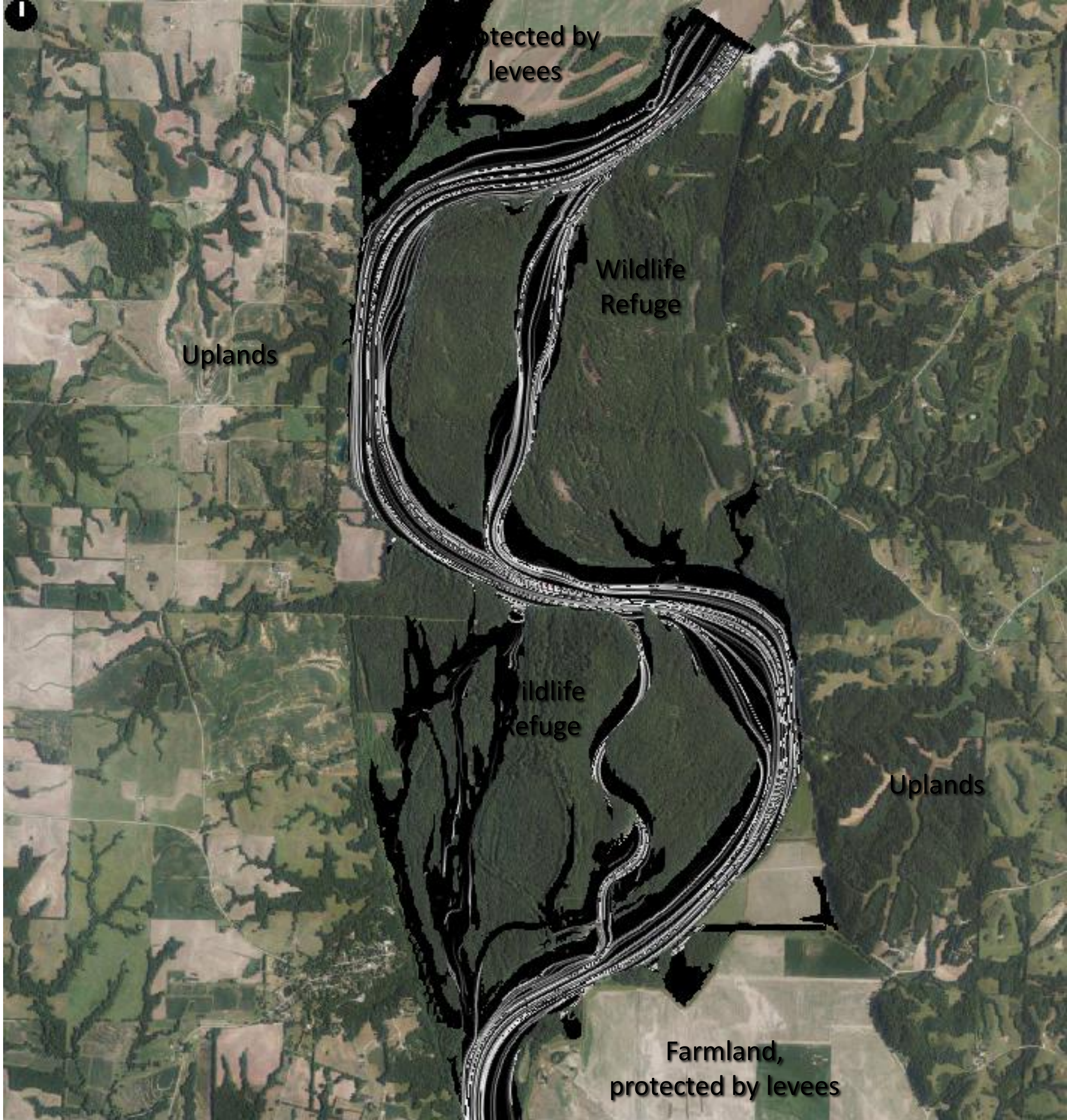
Lisbon-Jameson best-available example, lower lower river
Hydrodynamic habitat model. Flow is from left to right
35,000 cfs



**Lisbon – Jameson Complex**

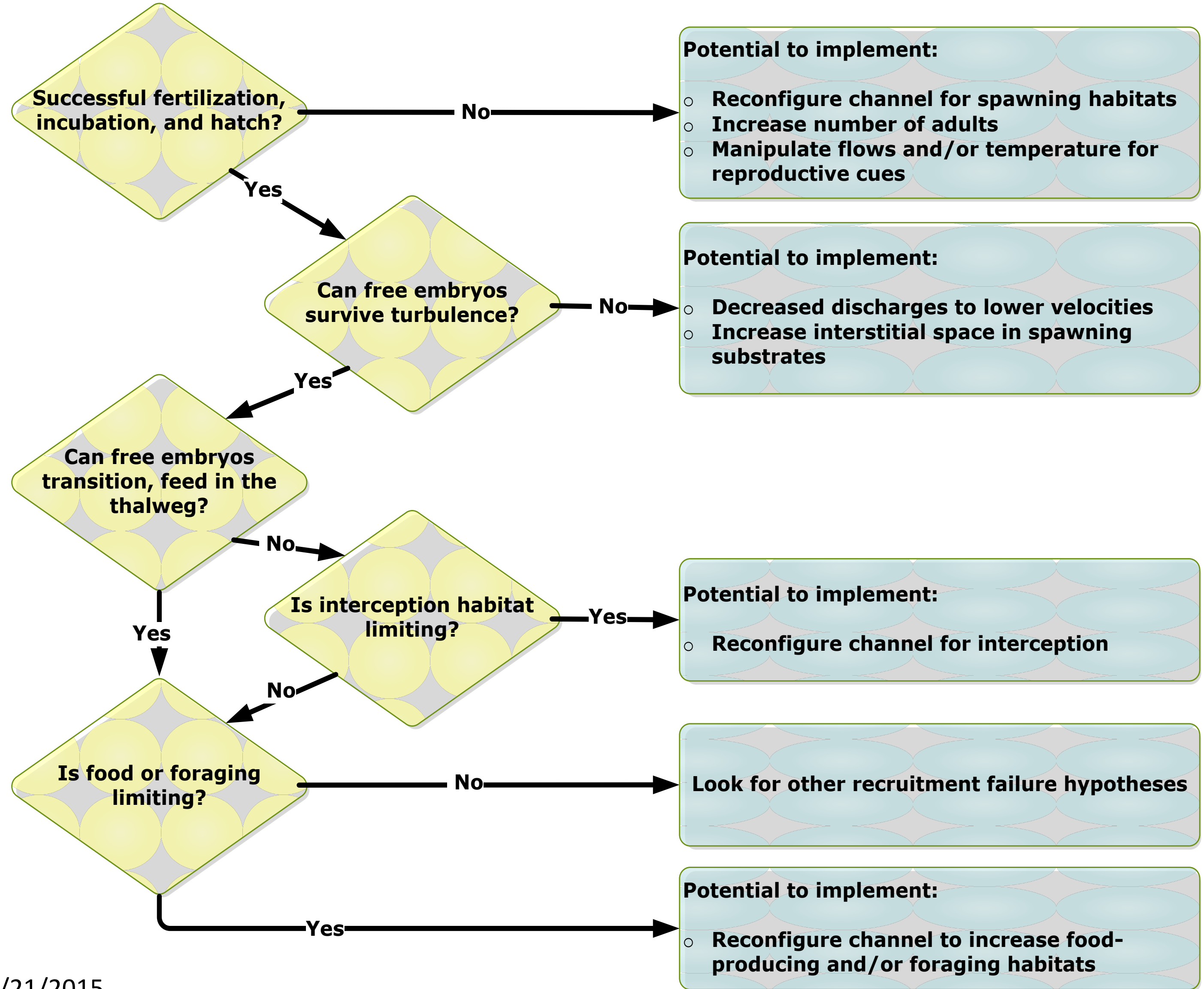
198,000 cubic feet per second
Exceeded 16 days per year on average

Just under flood stage



# Decision Trees

Engineer Research and Development Center



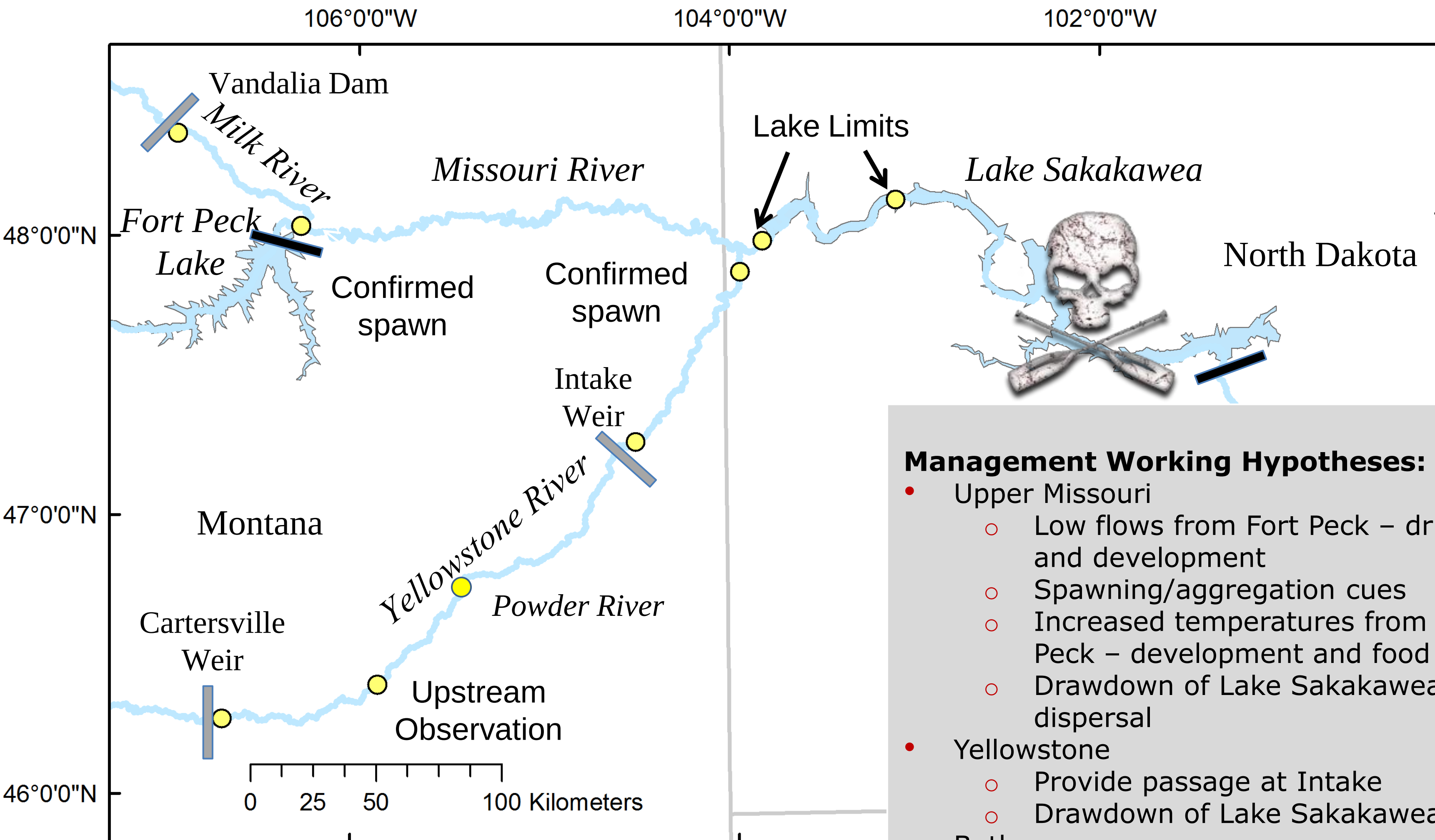
# Pallid Sturgeon Framework

Engineer Research and Development Center

| Level | Stocking | Spawning Habitat | Spawning Cues | Interception Habitat | Food Habitat | Foraging Habitat |
|---|---|---|---|---|---|---|
| 1 | Is limiting? Technical? | Is limiting? Technical? | Is limiting? Technical? | Is limiting? Technical? | Is limiting? Technical? | Is limiting? Technical? |
| 2 | Pilot effort | Pilot effort | Pilot effort | Pilot effort | Pilot effort | Pilot effort |
| 3 | Partial scale | Partial scale | Partial scale | Partial scale | Partial scale | Partial scale |
| 4 | Increase stocking | Create spawning habitat | Spring spawning cue flows | Create interception habitat | Create food producing habitat | Create foraging habitat |

# Free Embryo Drift and Survival
# Upper Missouri & Yellowstone Rivers

ERDC
Engineer Research and Development Center

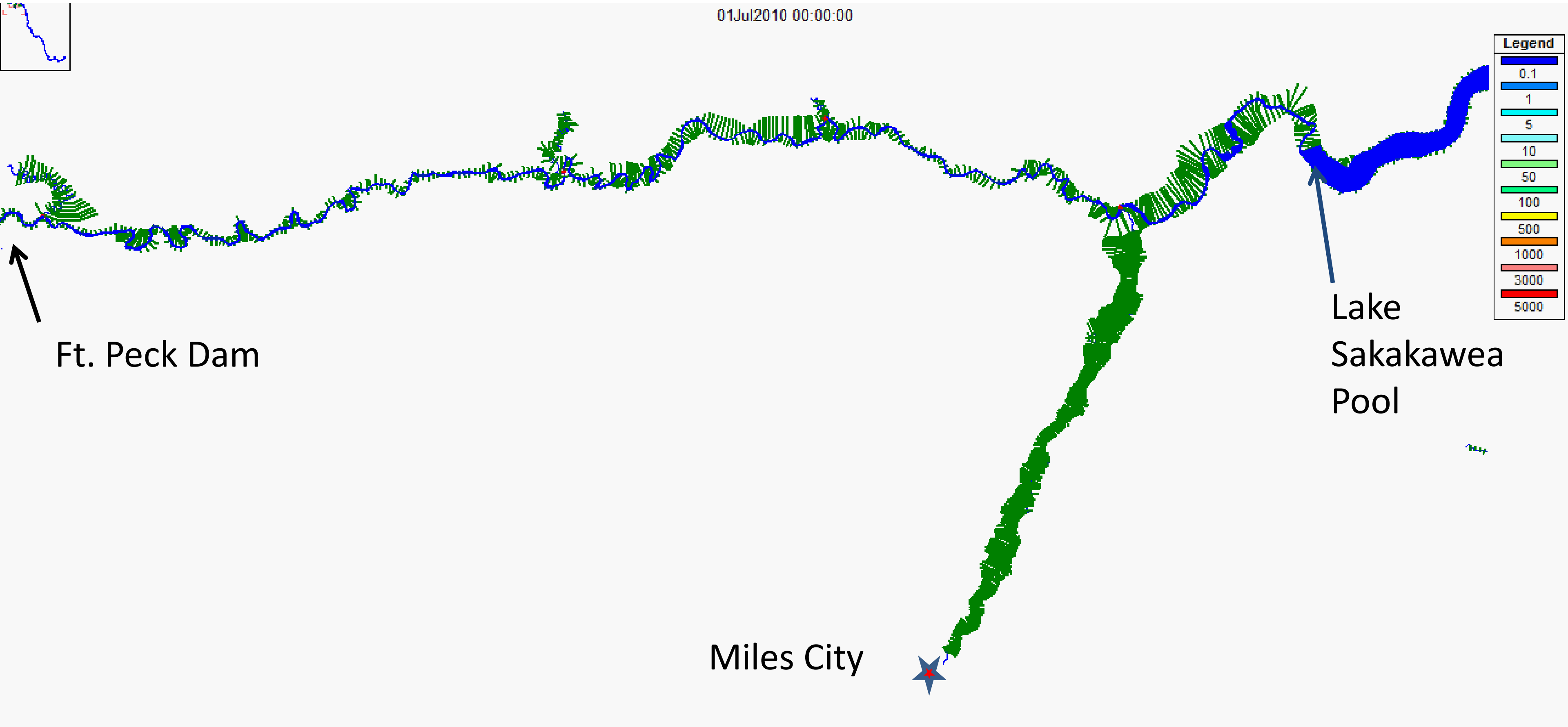



**Management Working Hypotheses:**

- Upper Missouri
  - Low flows from Fort Peck – drift and development
  - Spawning/aggregation cues
  - Increased temperatures from Fort Peck – development and food
  - Drawdown of Lake Sakakawea - dispersal
- Yellowstone
  - Provide passage at Intake
  - Drawdown of Lake Sakakawea
- Both
  - Stocking strategies
  - Genetic fitness

# 1D Advection/Dispersion

Engineer Research and Development Center



# Retention for 2003 – 2012; Spawn at Milk River Confluence

Engineer Research and Development Center

| Year | % Retained @ T=5 | % Retained @ T=6 | % Retained @ T=7 | % Retained @ T=8 | % Retained @ T=9 | % Retained @ T=10 |
|---|---|---|---|---|---|---|
| **2003** | 97 | 82 | 24 | 2 | 1 | 0 |
| **2004** | 99 | 100 | 79 | 29 | 7 | 3 |
| **2005** | 99 | 100 | 90 | 43 | 10 | 2 |
| **2006** | 99 | 98 | 71 | 23 | 6 | 3 |
| **2007** | 99 | 99 | 82 | 33 | 8 | 4 |
| **2008** | 100 | 99 | 76 | 26 | 4 | 0 |
| **2009** | 99 | 84 | 26 | 2 | 0 | 0 |
| **2010** | 80 | 20 | 3 | 0 | 0 | 0 |
| **2011** | 0 | 0 | 0 | 0 | 0 | 0 |
| **2012** | 84 | 17 | 0 | 0 | 0 | 0 |
| **Total** | **86** | **70** | **45** | **16** | **4** | **1** |

# Preliminary Effectiveness of Management Actions

ERDC Engineer Research and Development Center

| Percent Larvae U/S of Pool at T = 4 Days | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Lake Sakakawea Pool Level | | | | | |
| Flow | | HMin | Min | 10 | 50 | 90 | Max |
| Exceed | Ft. Peck | 1805.0 | 1812.6 | 1821.6 | 1843.2 | 1850.4 | 1856.0 |
| Min | 3000 | 100% | 100% | 100% | 100% | 100% | 100% |
| 5 | 5500 | 100% | 100% | 100% | 100% | 100% | 100% |
| 10 | 6100 | 100% | 100% | 100% | 100% | 100% | 100% |
| 25 | 7150 | 100% | 100% | 100% | 100% | 99% | 99% |
| 50 | 8600 | 99% | 99% | 99% | 99% | 99% | 97% |
| 75 | 11000 | 100% | 100% | 100% | 100% | 98% | 92% |
| 90 | 14400 | 100% | 100% | 100% | 100% | 95% | 80% |
| 95 | 16100 | 100% | 100% | 100% | 100% | 89% | 63% |

| Percent Larvae U/S of Pool at T = 6 Days | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Lake Sakakawea Pool Level | | | | | |
| Flow | | HMin | Min | 10 | 50 | 90 | Max |
| Exceed | Ft. Peck | 1805.0 | 1812.6 | 1821.6 | 1843.2 | 1850.4 | 1856.0 |
| Min | 3000 | 100% | 100% | 100% | 98% | 85% | 70% |
| 5 | 5500 | 100% | 100% | 97% | 80% | 33% | 22% |
| 10 | 6100 | 100% | 99% | 96% | 75% | 23% | 14% |
| 25 | 7150 | 99% | 98% | 91% | 60% | 11% | 6% |
| 50 | 8600 | 98% | 96% | 85% | 49% | 6% | 4% |
| 75 | 11000 | 98% | 94% | 83% | 44% | 3% | 1% |
| 90 | 14400 | 92% | 86% | 68% | 30% | 2% | 0% |
| 95 | 16100 | 85% | 76% | 57% | 20% | 1% | 0% |

| Percent Larvae U/S of Pool at T = 8 Days | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Lake Sakakawea Pool Level | | | | | |
| Flow | | HMin | Min | 10 | 50 | 90 | Max |
| Exceed | Ft. Peck | 1805.0 | 1812.6 | 1821.6 | 1843.2 | 1850.4 | 1856.0 |
| Min | 3000 | 92% | 85% | 60% | 26% | 7% | 3% |
| 5 | 5500 | 53% | 41% | 14% | 6% | 1% | 1% |
| 10 | 6100 | 47% | 34% | 11% | 4% | 0% | 1% |
| 25 | 7150 | 29% | 20% | 6% | 2% | 0% | 0% |
| 50 | 8600 | 16% | 11% | 3% | 1% | 0% | 1% |
| 75 | 11000 | 12% | 8% | 2% | 0% | 0% | 0% |
| 90 | 14400 | 5% | 3% | 1% | 0% | 0% | 0% |
| 95 | 16100 | 3% | 2% | 1% | 0% | 0% | 0% |

| Percent Larvae U/S of Pool at T = 10 Days | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Lake Sakakawea Pool Level | | | | | |
| Flow | | HMin | Min | 10 | 50 | 90 | Max |
| Exceed | Ft. Peck | 1805.0 | 1812.6 | 1821.6 | 1843.2 | 1850.4 | 1856.0 |
| Min | 3000 | 21% | 19% | 6% | 3% | 1% | 1% |
| 5 | 5500 | 4% | 5% | 1% | 1% | 0% | 0% |
| 10 | 6100 | 0% | 3% | 1% | 0% | 0% | 0% |
| 25 | 7150 | 1% | 1% | 1% | 0% | 0% | 0% |
| 50 | 8600 | 0% | 0% | 0% | 0% | 0% | 0% |
| 75 | 11000 | 0% | 0% | 0% | 0% | 0% | 0% |
| 90 | 14400 | 0% | 0% | 0% | 0% | 0% | 0% |
| 95 | 16100 | 0% | 0% | 0% | 0% | 0% | 0% |

# Reserve Slides for Questions

Engineer Research and Development Center

# Near-Term Activities

Engineer Research and Development Center

- Assist with establishment of targets
- Alternative development support
  - Identification/refinement
  - Effectiveness & trade-offs
- Adaptive management plan development
  - Hypothesis refinement, organization, prioritization
  - Decision-making and analysis process
- Hypothesis testing/data analysis
- Additional drift modeling (interception?)
- ESH model updates
  - New protocol for image processing & classification
  - Addition of vegetation component
  - Alternative time steps

# Acknowledgements


**EA Co-PIs:**

| | |
|---|---|
| Kate Buenau | PNNL |
| Robb Jacobson | USGS |

**Work Team:**

| | |
|---|---|
| Craig Fischenich | ERDC |
| Stan Gibson | HEC |
| John Hickey | HEC |
| Jeff Tripe | Corps |
| Dan Pridal | Corps |
| Don Meier | Corps |
| Tom Econopouly | USFWS |

**Others:** A large cast of District, and outside SMEs

**Cadre:**

| | |
|---|---|
| Paul Boyd | Corps |
| Jean Reed | Corps |
| Ryan Larsen | Corps |
| Christine Cieslik | Corps |
| Marian Baker | Corps |
| Emily Nziramasanga | Corps |
| Joshua Mellinger | Corps |
| Travis Yonts | Corps |
| Michelle Whitney | Corps |
| Doug Clemetson | Corps |
| Doug Latka | Corps |
| Nate Clifton | ERDC |
| Bobby McComas | ERDC |
| David Smith | ERDC |

# EWN Essential Elements

Engineer Research and Development Center

- ✓ Use science and engineering to produce operational efficiencies supporting sustainable project benefits.
- ✓ Use natural processes to maximum benefit, thereby reducing demands on limited resources, minimizing the environmental footprint of projects.
- ✓ Broaden and extend the base of benefits provided by projects to include substantiated economic, social, and environmental benefits.
- ✓ Use science-based collaborative processes to organize and focus interests, stakeholders, and partners to reduce social friction, resistance, and project delays while producing more broadly acceptable projects.

# EWN Principles

Engineer Research and Development Center

- ✓ **Holistic** – an ecosystem approach for planning, designing, constructing and operating projects where social, economic and environmental factors are equitably weighed in the decision making process.
- ✓ **A Systems Approach** – reflecting the reality that USACE projects exist in complex physical and social/cultural systems, and that a single action influences many other parts of the system.
- ✓ **Sustainable** – focused on the long-term sustainability and resilience of project solutions and the benefits streams provided by the system over time.
- ✓ **Science-based** – built on first understanding, then working deliberately with natural forces and processes to accomplish engineering goals.
- ✓ **Collaborative** – based on effective partner and stakeholder communication, engagement and collaboration through the entire life cycle of a project, beginning at the earliest conceptual stages.

# EWN Principles (concluded)

Engineer Research and Development Center

- ? **Efficient and cost effective** – reducing time and rework, while minimizing social friction.
- ✓ **Socially responsive** – aligned with the values, objectives, interests and priorities of USACE, partners, stakeholders and society at large.
- ✓ **Innovative** – embracing new and emerging technologies and incorporating continuous learning, technology transfer and adoption of new and leading practices.
- ✓ **Adaptive** – demonstrating adaptive attitudes, structures and processes that enable a living, evolving and sustainable practice.

# Background

Engineer Research and
Development Center

# Background

Engineer Research and Development Center

## What is an Effects Analysis?

"Evaluation of the effects of a federal agency action that has the potential to harm a listed species…

The framework includes three essential steps:

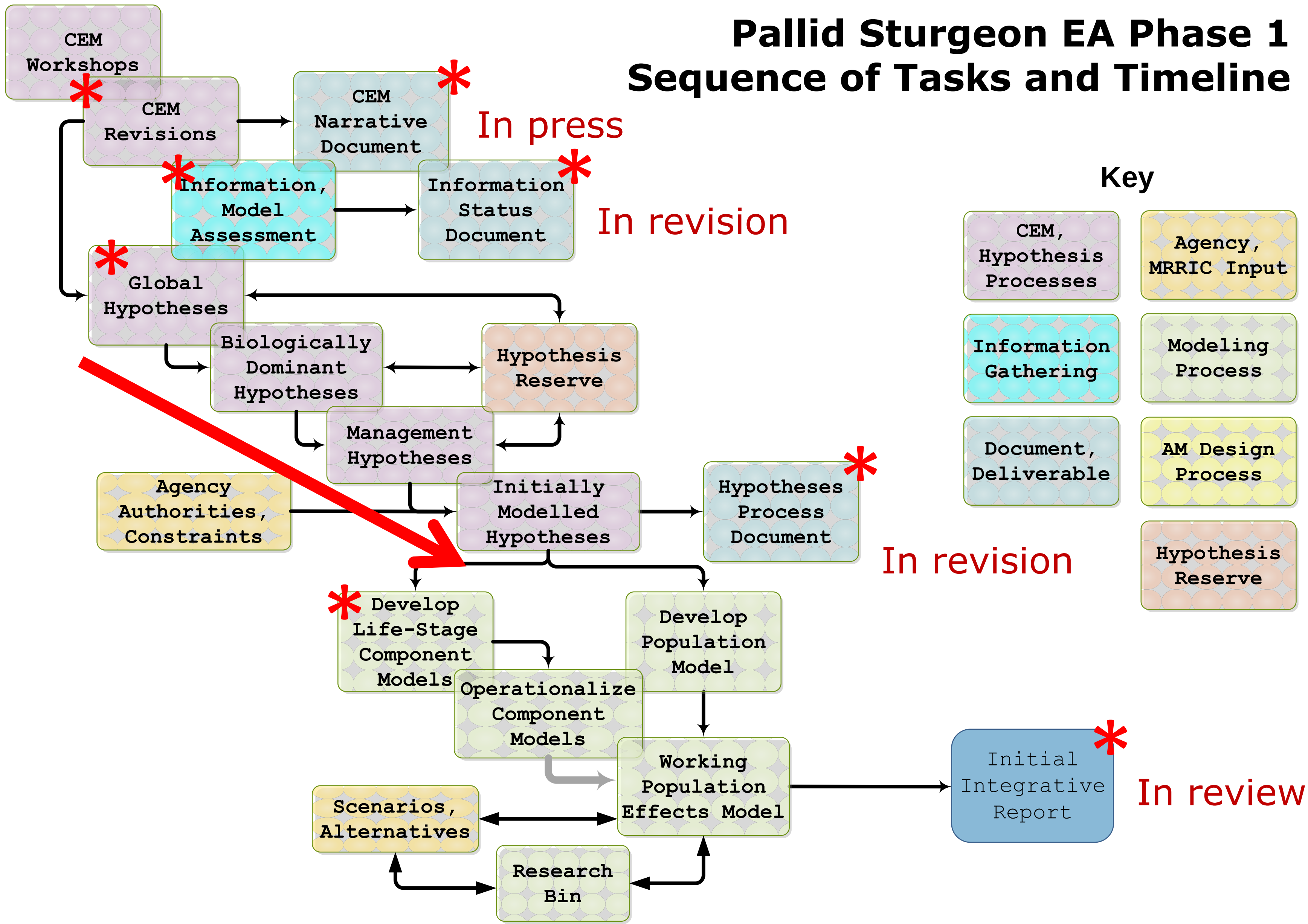
- the collection of reliable scientific information,
- the critical assessment and synthesis of available data and analyses derived from those data,
- and the analysis of the effects of actions on listed species and their habitats"

## Three Teams:

- Hydrology, hydraulics, geomorphology (Craig Fischenich)
- Plovers and terns (Kate Buenau)
- Pallid sturgeon (Robb Jacobson)

Murphy, D., and Weiland, P., 2011, The Route to Best Science in Implementation of the Endangered Species Act's Consultation Mandate: The Benefits of Structured Effects Analysis: Environmental Management, v. 47, no. 2, p. 161-172. 10.1007/s00267-010-9597-9.

# Pallid Sturgeon EA Phase 1
# Sequence of Tasks and Timeline



# Model Framework Scope

Engineer Research and Development Center

**Geographic:** Missouri River from Ft. Peck to St. Louis, including the lower Yellowstone River

**Temporal:** Forecast conditions for 30-50 years

**Resolution:** Dictated by species requirements and the processes and actions simulated

**Assessment Capabilities:** Includes, but is not limited to, management actions identified in the BiOp

**Other:** Support the broader management planning effort and future adaptive management needs by developing and employing models that can be used to support those purposes

# H&H Modeling Backbone

ERDC
Engineer Research and Development Center

## HEC-ResSim

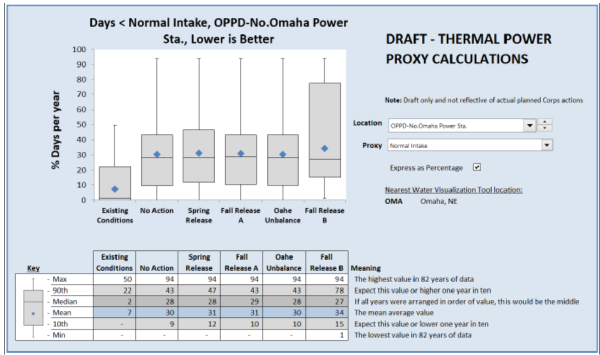
- Simulates reservoir storage , pool levels, releases and downstream flows based on inflow, depletions, evaporation and reservoir operation criteria. The model will allow simulation of multiple reservoirs as a system.
- Used for comparing impacts/benefits of operational alternatives. Also used to provide input to sturgeon habitat, ESH, EFM and HEC-RAS models.

## HEC-RAS

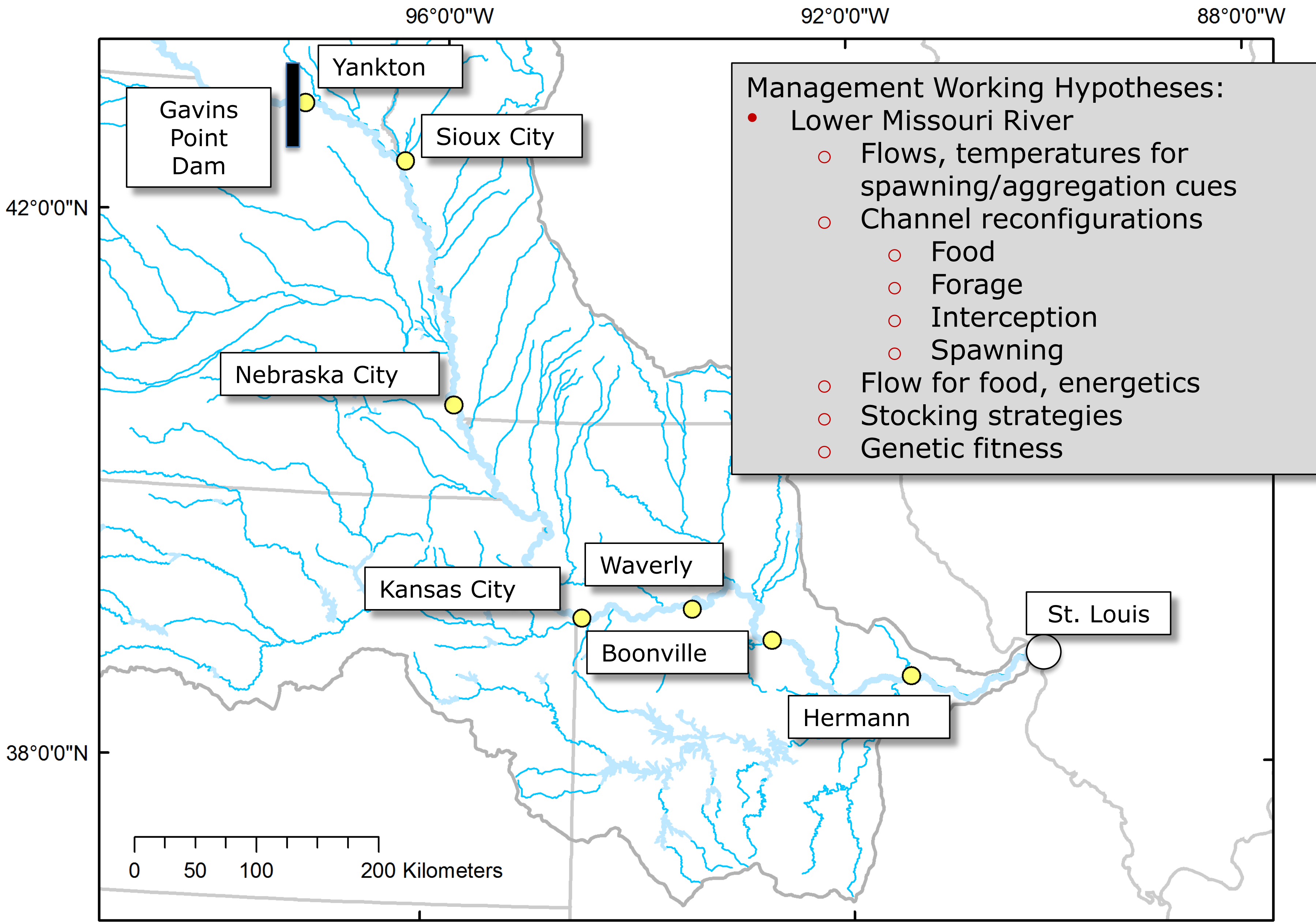
- Simulates one-dimensional steady and unsteady flow and changes in river stage, flow rate, and storage areas in the river and floodplain over time and by transect/river mile. Stage, flow, and other hydraulic data provides inputs to the species models (and HC analyses).
- The software also has capabilities for sediment modeling, water temperature analysis, and water quality modeling.

## HEC-EFM

- Used to assess spatial/statistical outcomes




| Key | Existing Conditions | No Action | Spring Release | Fall Release A | Oahe Unbalance | Fall Release B | Meaning |
|---|---|---|---|---|---|---|---|
| Max | 50 | 94 | 94 | 94 | 94 | 94 | The highest value in 82 years of data |
| 90th | 22 | 43 | 47 | 43 | 43 | 78 | Expect this value or higher one year in ten |
| Median | 2 | 28 | 28 | 29 | 28 | 27 | If all years were arranged in order of value, this would be the middle |
| Mean | 7 | 30 | 31 | 31 | 30 | 34 | The mean average value |
| 10th | - | 9 | 12 | 10 | 10 | 15 | Expect this value or lower one year in ten |
| Min | - | - | - | - | - | 1 | The lowest value in 82 years of data |

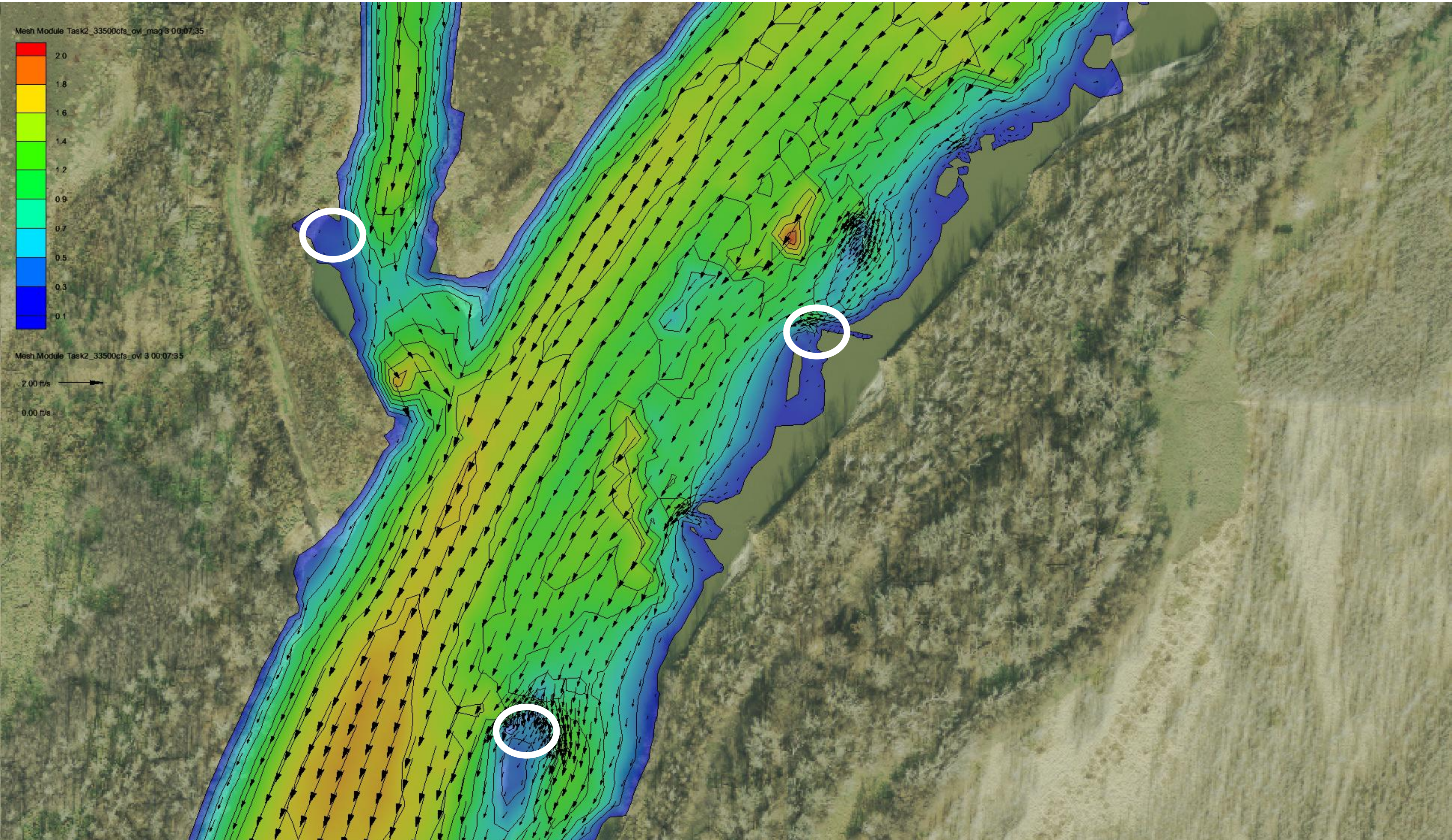

96°0'0"W
92°0'0"W
88°0'0"W
42°0'0"N
38°0'0"N
Yankton
Gavins Point Dam
Sioux City
Nebraska City
Kansas City
Waverly
Boonville
Hermann
St. Louis
0 50 100 200 Kilometers
Management Working Hypotheses:
Lower Missouri River
Flows, temperatures for spawning/aggregation cues
Channel reconfigurations
Food
Forage
Interception
Spawning
Flow for food, energetics
Stocking strategies
Genetic fitness

# Modeling of Free Embryo Drift

Engineer Research and Development Center

# Particle Trapping

Engineer Research and Development Center



# Lower River (Gavins Pt. – St. Louis)

Engineer Research and Development Center

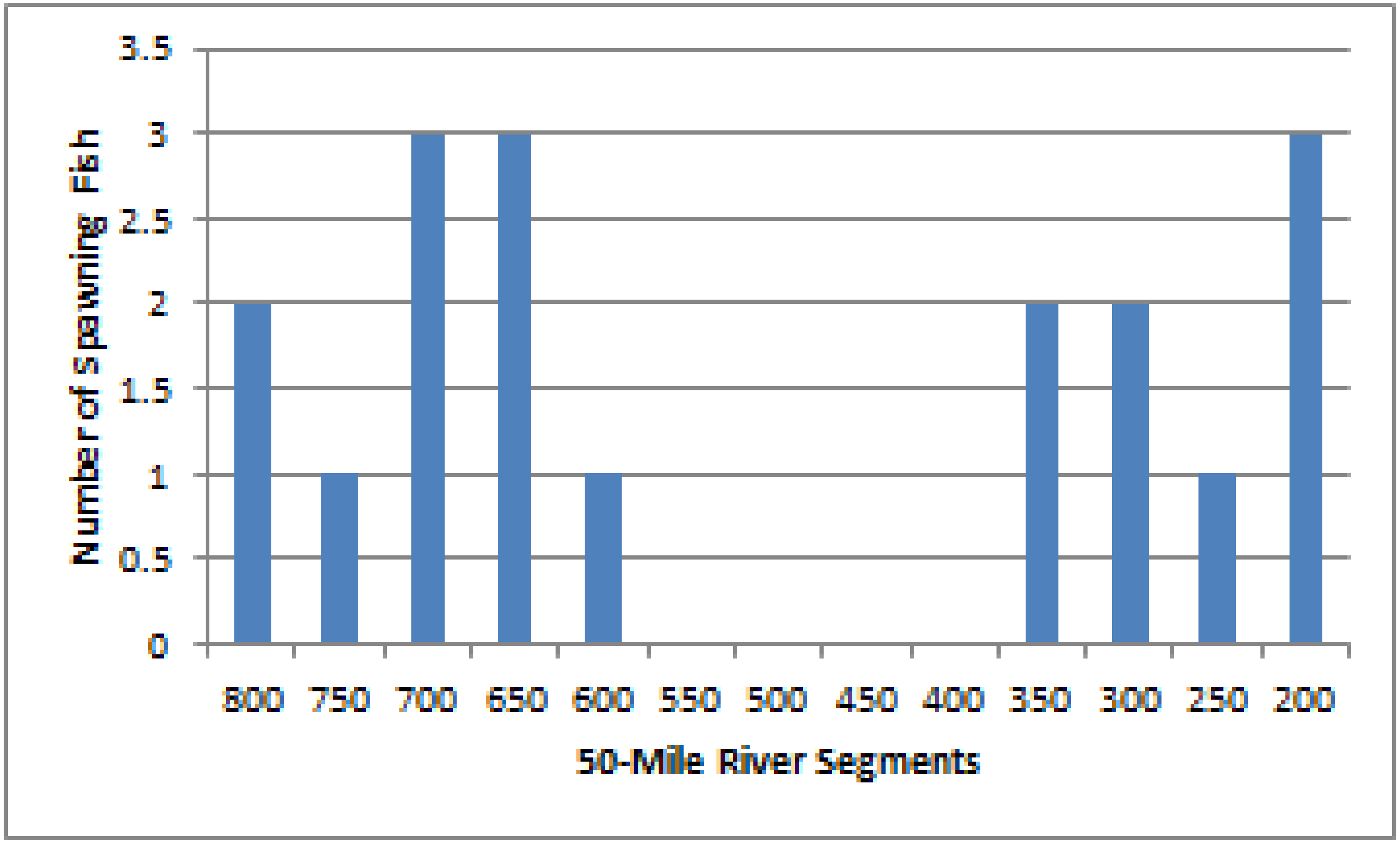



Figure 32. Probable spawning locations on the lower river, grouped in 50-mile segments, 2007 - 2012. (information based on telemetry data provided by USGS).

# Free Embryo Drift (RM600)

ERDC
Engineer Research and Development Center

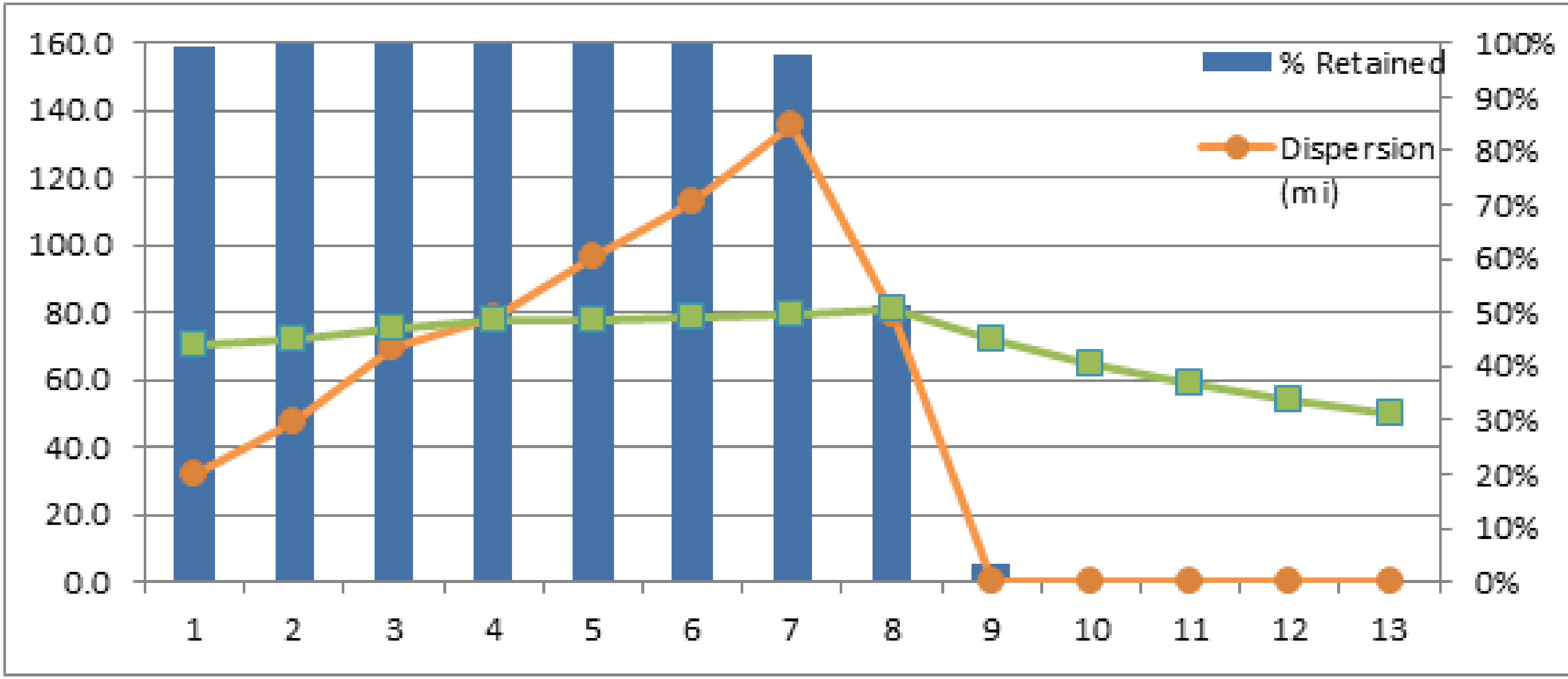
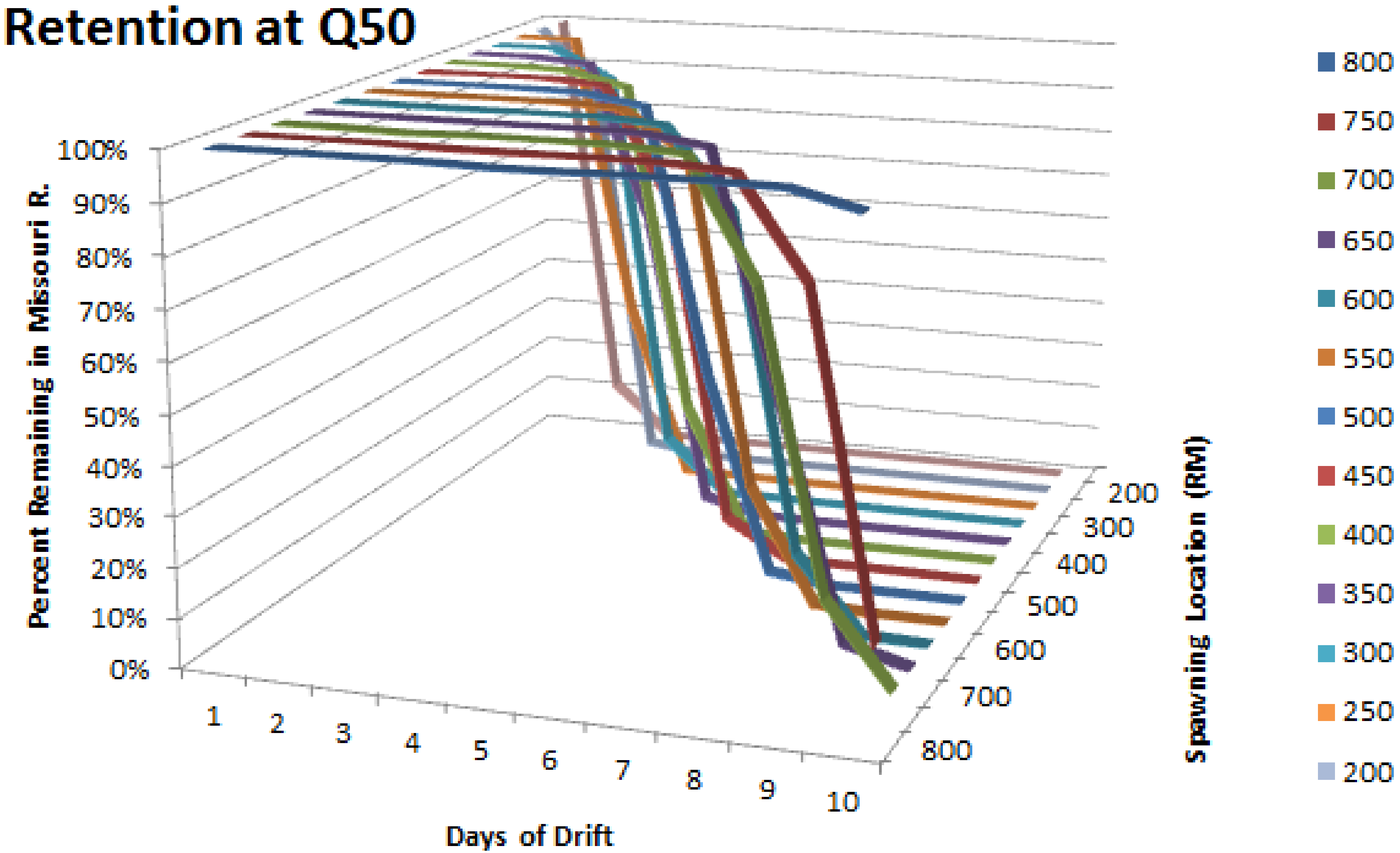


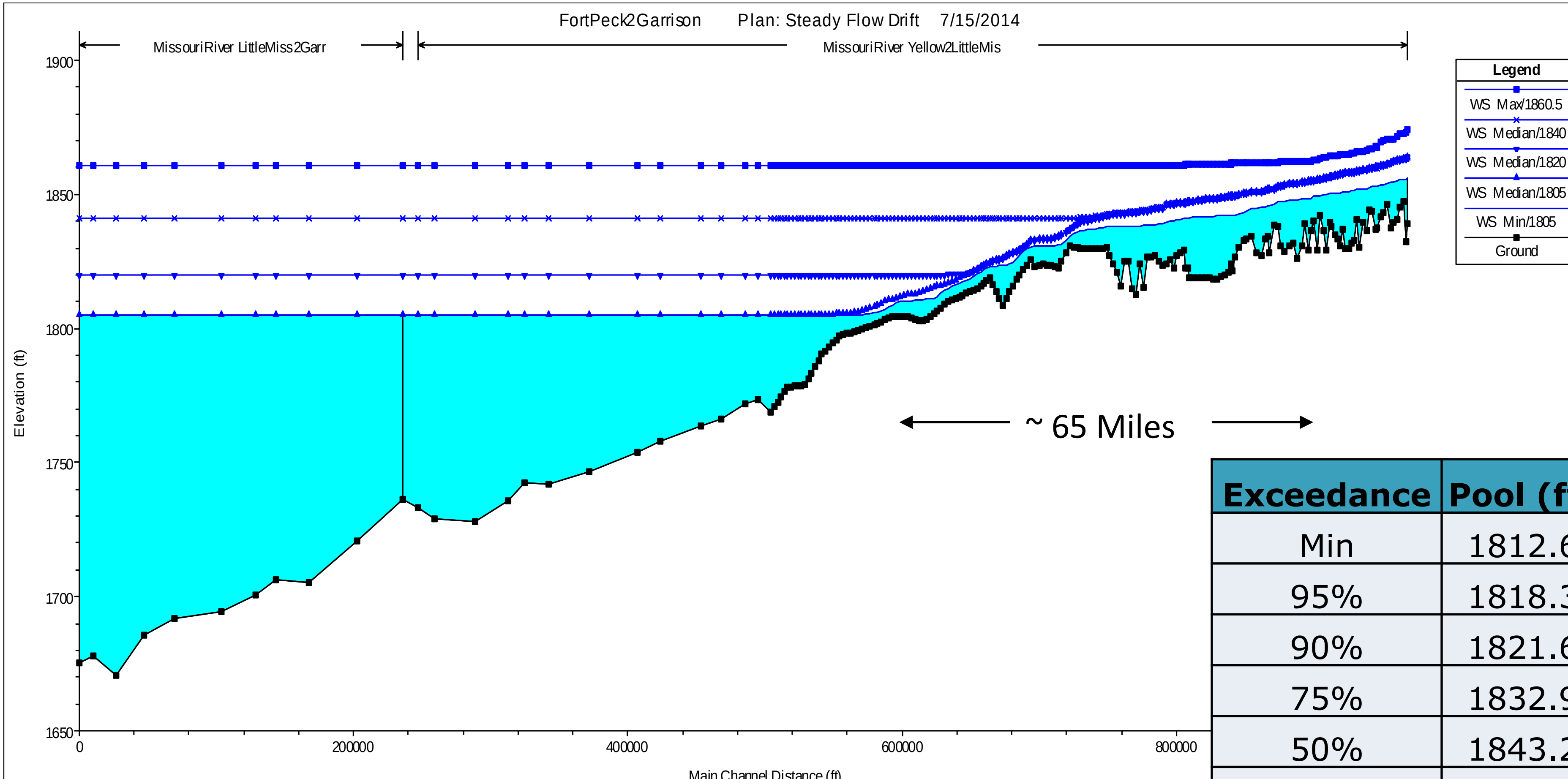

Figure 43. Retention, advection and dispersion for median June/July flows with drift initiated at RM 600 (Platte River Confluence). (Note: Need to correct and update this figure)

# Retention/Distribution

Engineer Research and Development Center



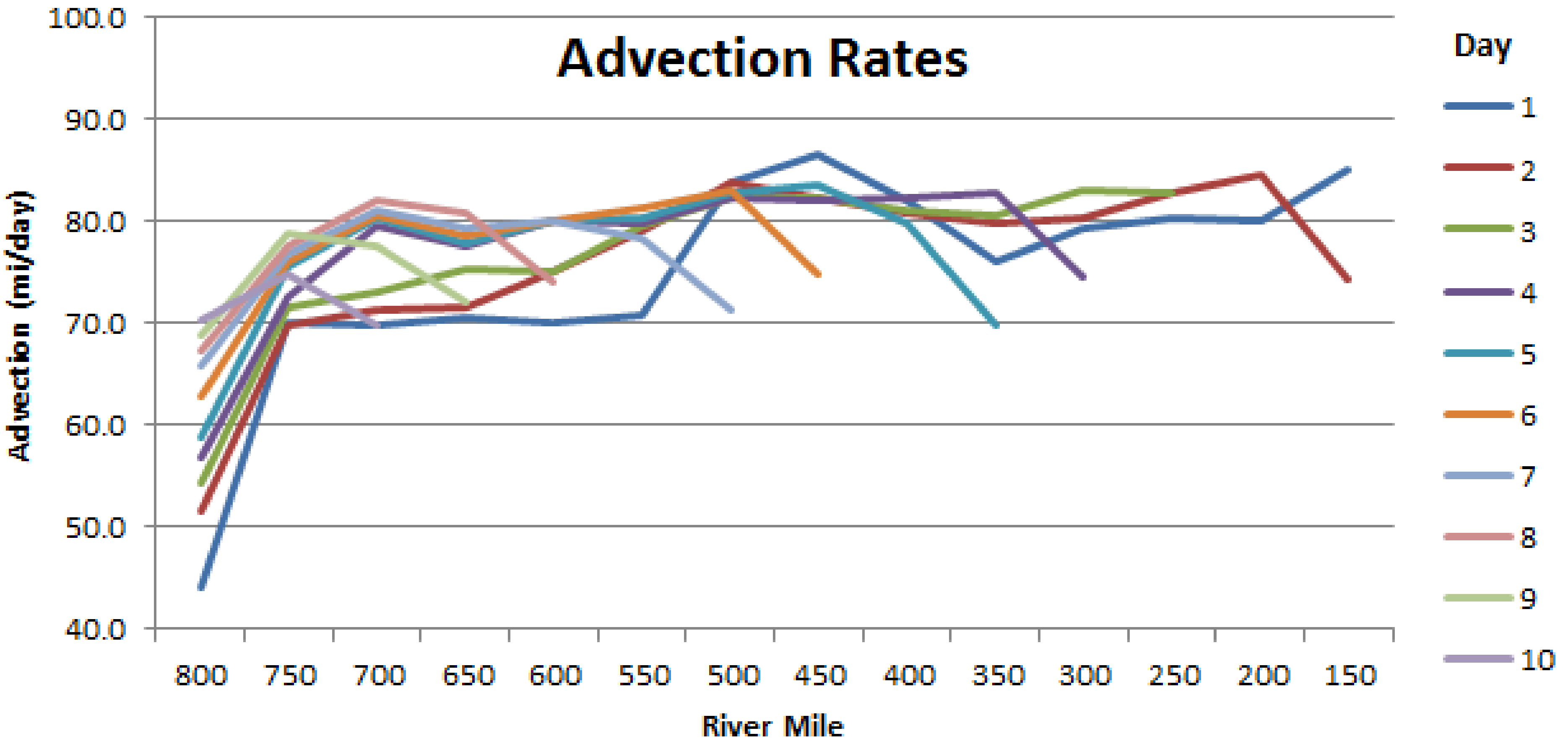
# Lake Sakakawea Pool Levels



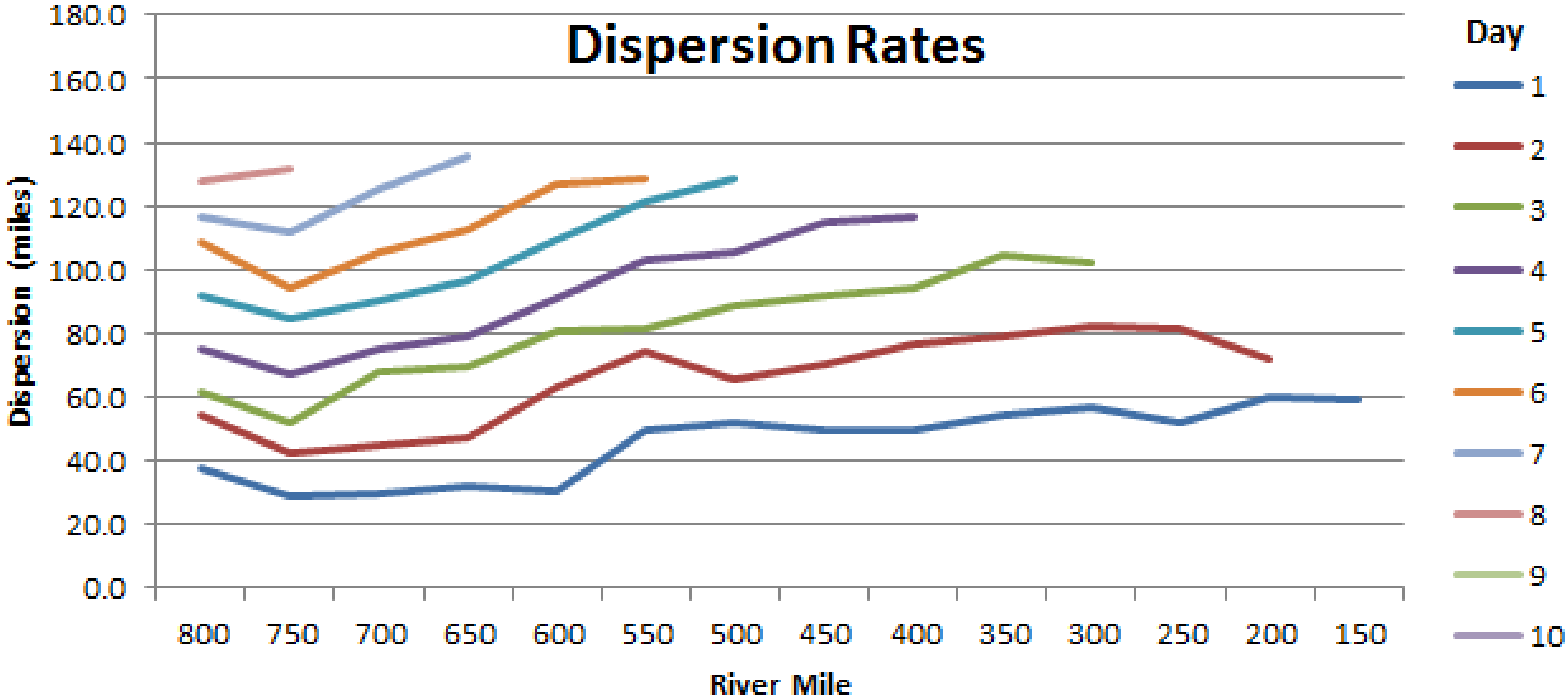

| Exceedance | Pool (ft) |
|---|---|
| Min | 1812.6 |
| 95% | 1818.3 |
| 90% | 1821.6 |
| 75% | 1832.9 |
| 50% | 1843.2 |
| 25% | 1848.4 |
| 10% | 1850.4 |
| 5% | 1852.9 |
| Max | 1855.9 |

# Advection Rates Q50

ERDC
Engineer Research and Development Center



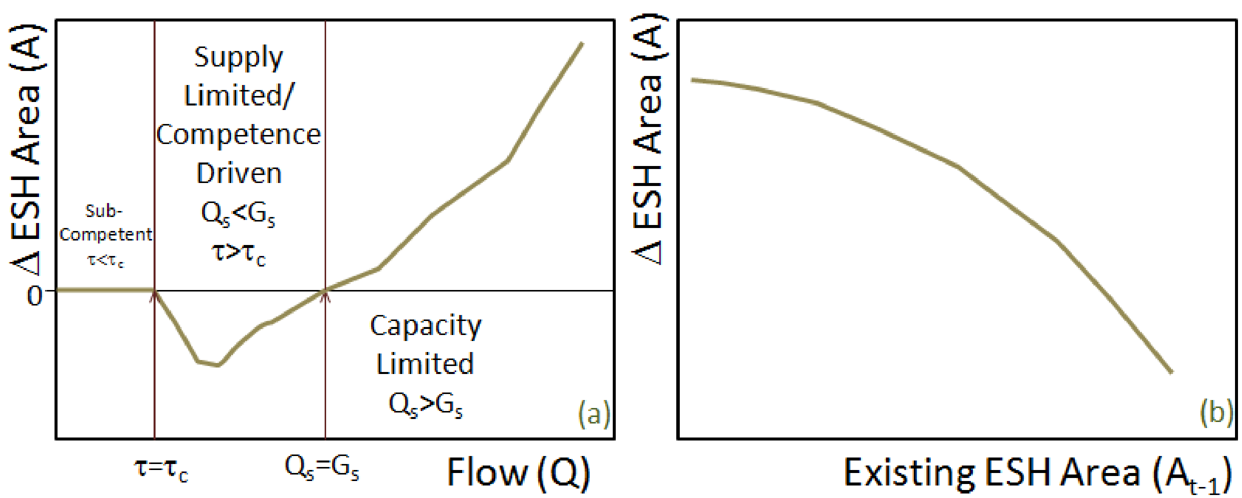
# Dispersion Rates
## (at Q50 for Spawning Sites on 50-mi Increments)



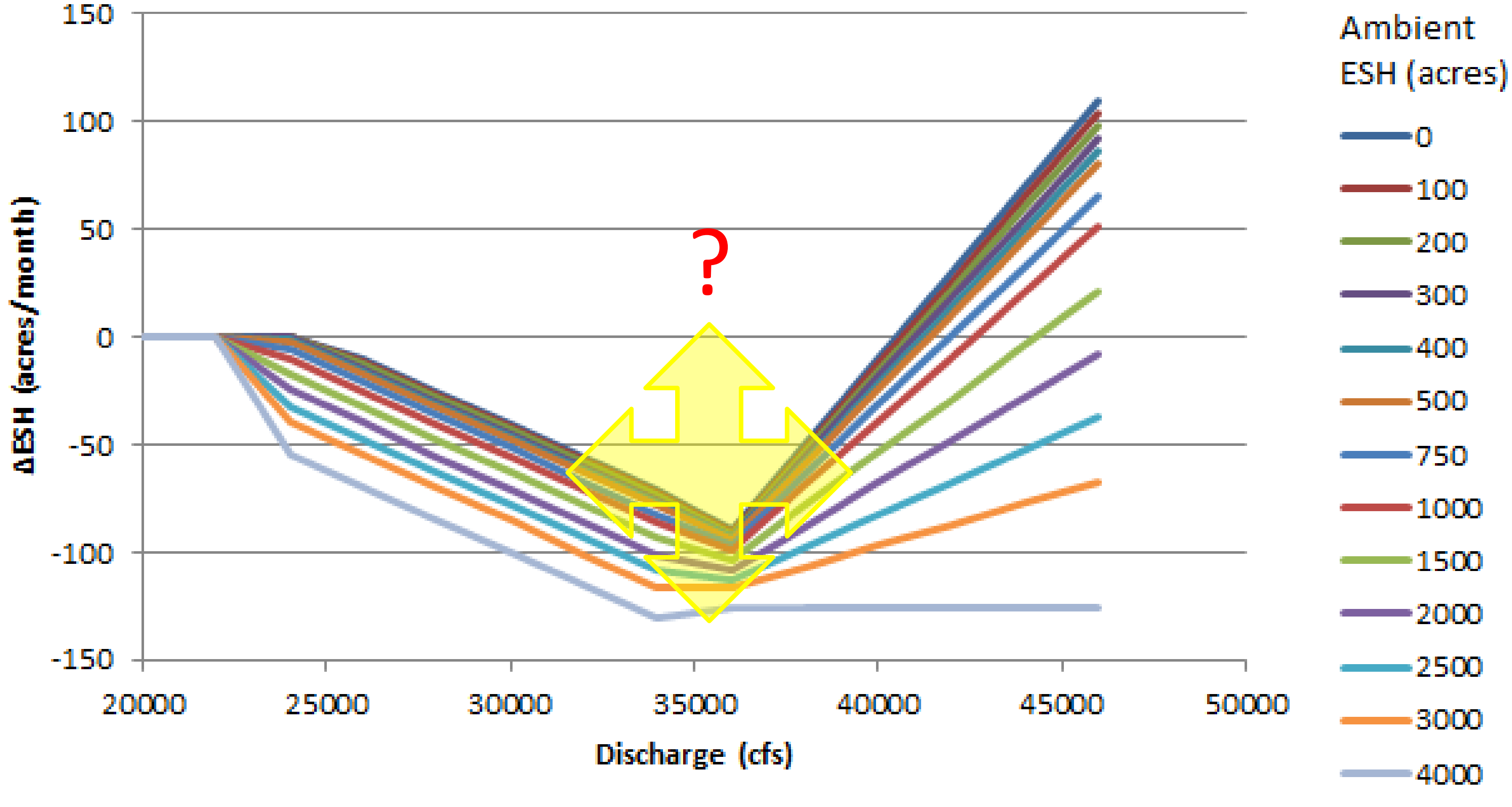
# ESH Conceptual Model

Engineer Research and Development Center

- Supply limited and competence driven
- Critical thresholds for erosion and transport
- Ambient ESH area affects response function
- $A \sim f\,(Q, d, A_{t-1})$

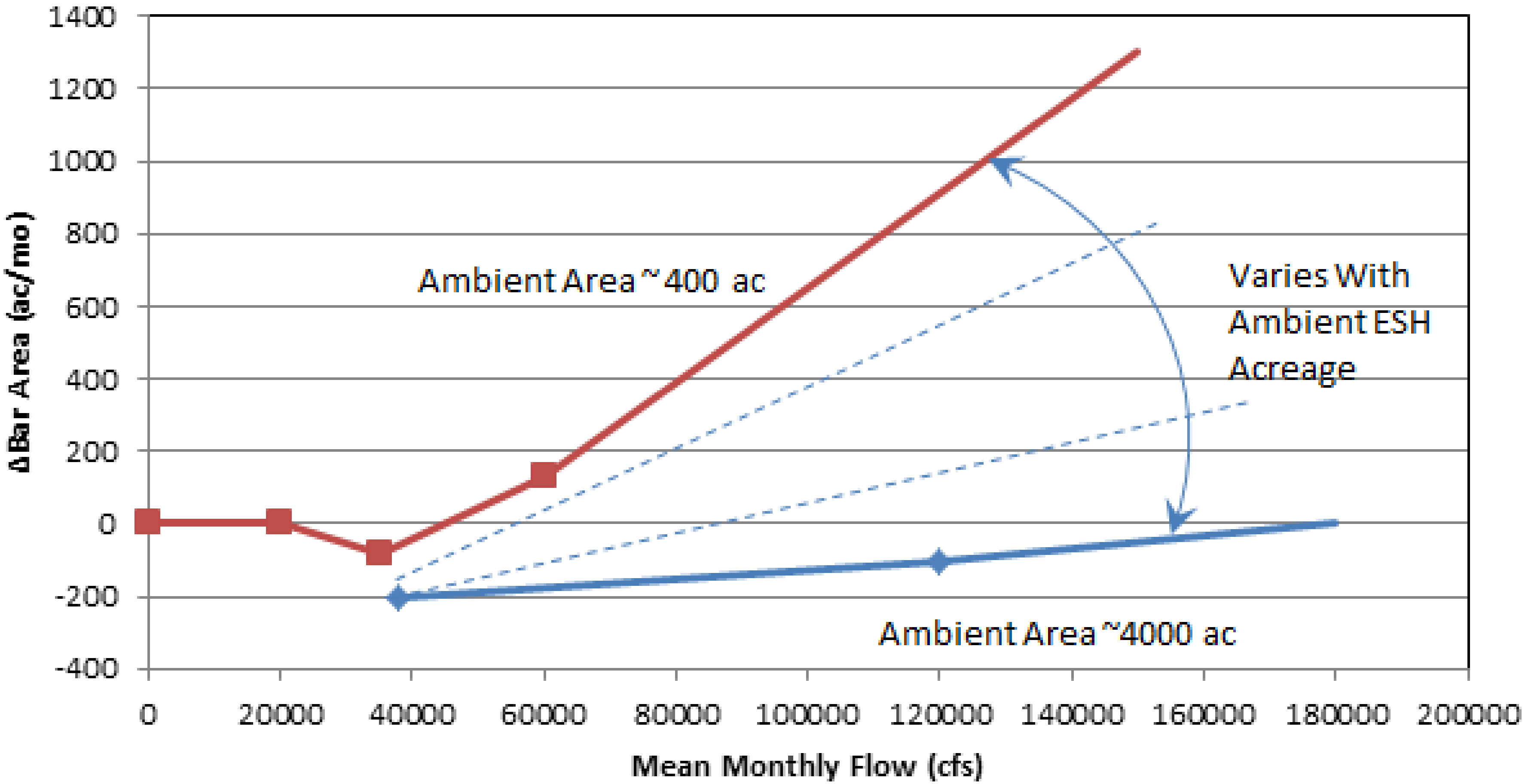


# Model Construct



# Parameterization

Assumption: Change in ESH due to flow magnitude and/or duration depends on ambient conditions

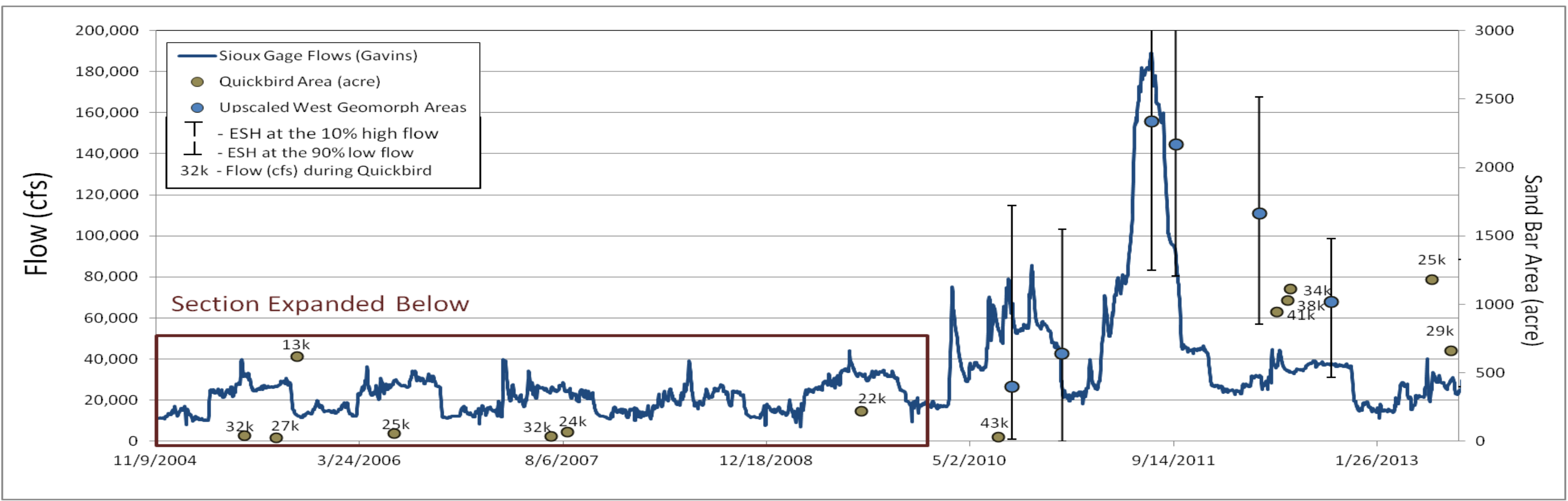


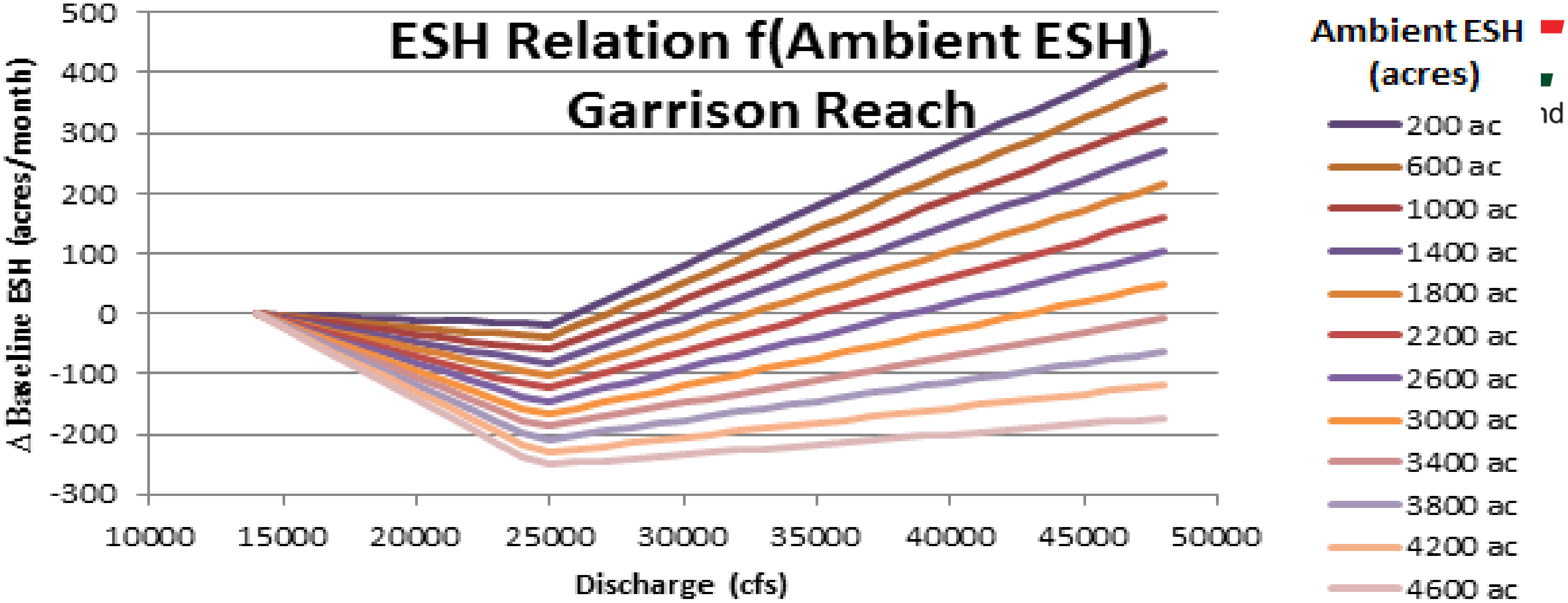
# Empirical Data

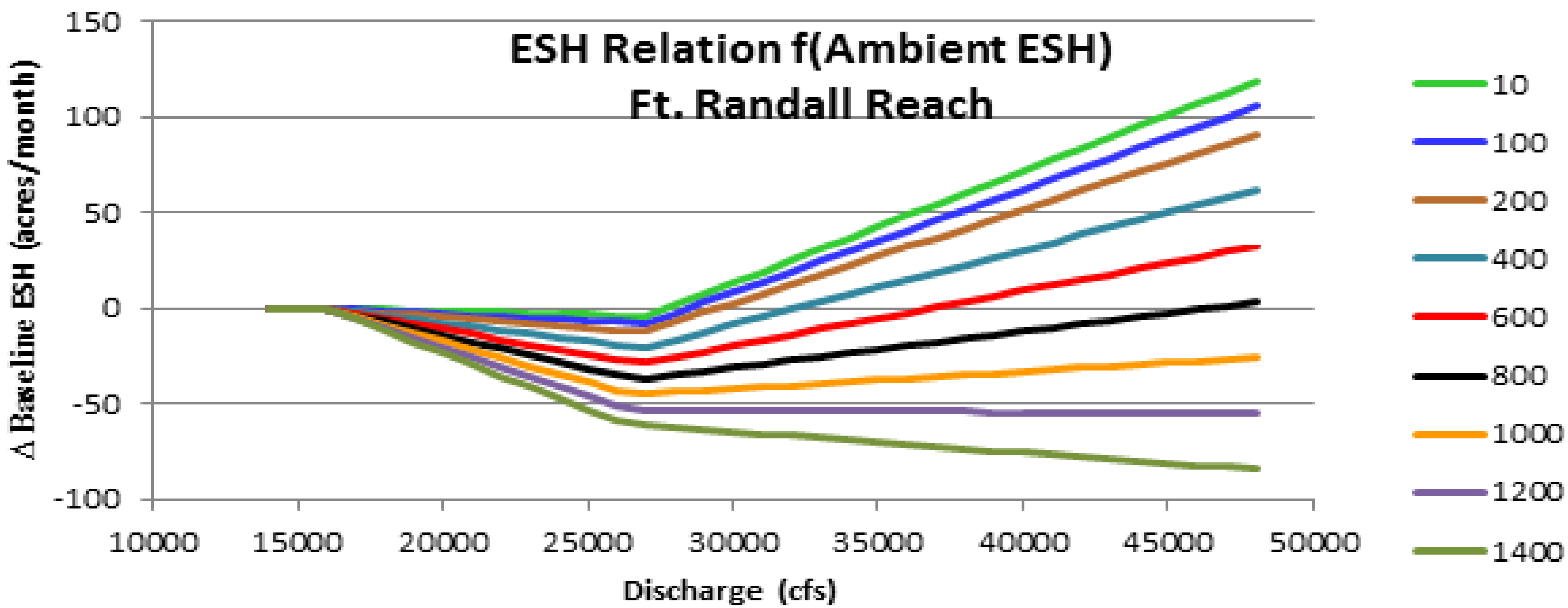
ERDC
Engineer Research and Development Center

| | WEST (2014) NWO Geomorph Study | QuickBird (USGS – Strong, 2007, 2012) |
|---|---|---|
| **Coverage** | Six 0.5-1 mile sections in the Gavin's Reach (8% of the reach) | Total coverage of Gavins and Garrison Reaches |
| **Temporal Coverage** | Seven measurement between 2010 and 2013, concentrating on the aftermath of 2010 elevated flow and the 2011 flood. | Thirteen coverage between 2005 and 2013. |
| **Flow Control** | ESH measurements independent of flow at time of measurement. | ESH measurements dependent on flow (e.g. higher flows return smaller ESH) |

Supplemental data: Biedenharn et al. (2001), Elliott et al. (2006) and USACE (2013)




ESH Relation f(Ambient ESH)
Garrison Reach
Δ Baseline ESH (acres/month)
500
400
300
200
100
0
-100
-200
-300
10000
15000
20000
25000
30000
35000
40000
45000
50000
Discharge (cfs)
Ambient ESH (acres)
200 ac
600 ac
1000 ac
1400 ac
1800 ac
2200 ac
2600 ac
3000 ac
3400 ac
3800 ac
4200 ac
4600 ac


ESH Relation f(Ambient ESH)
Ft. Randall Reach
Δ Baseline ESH (acres/month)
150
100
50
0
-50
-100
10000
15000
20000
25000
30000
35000
40000
45000
50000
Discharge (cfs)
10
100
200
400
600
800
1000
1200
1400

# Algorithms

Engineer Research and Development Center

**Gavins Point:**

$$A_t^* = A_{t-1}^* + \begin{cases} 0, & \&Q \le 22,000\ cfs \\ -0.0076Q + 168 + .015(1300 - A_{t-1}^*), & 22\text{k} < Q \le 35k\ cfs \\ (-0.0000046A_{t-1}^* + 0.02)Q + 0.171A_{t-1}^* - 810, & \&Q > 35,000\ \text{cfs} \end{cases}$$

**Garrison:**

$$A_t^* = A_{t-1}^* + \begin{cases} 0, & \&Q \le 13,000\ cfs \\ (\text{Q} - 13000) * (-0.000005A_{t-1}^* - 0.0006), & 13\text{k} < Q \le 25k\ cfs \\ (-0.0000037A_{t-1}^* + 0.02)Q + 0.0396A_{t-1}^* - 517, & \&Q > 25,000\ \text{cfs} \end{cases}$$

**Ft. Randall:**

$$A_t^* = A_{t-1}^* + \begin{cases} 0, & \&Q \le 16,000\ cfs \\ (\text{Q} - 16000) * (-0.0000035A_{t-1}^* - 0.0003), & 16\text{k cfs} < Q \le 28k\ cfs \\ (-0.000005A_{t-1}^* + 0.0059)Q + 0.094A_{t-1}^* - 163, & \&Q > 28,000\ \text{cfs} \end{cases}$$

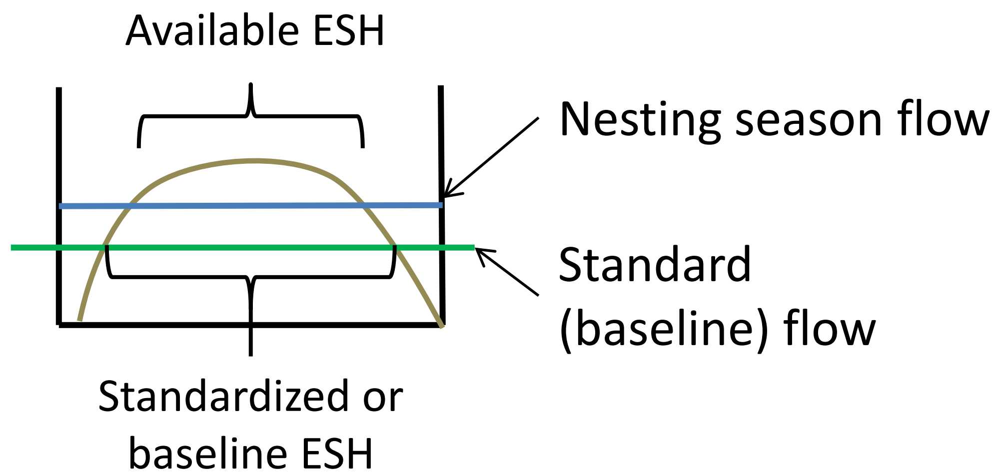
# Hydrology for Assessments

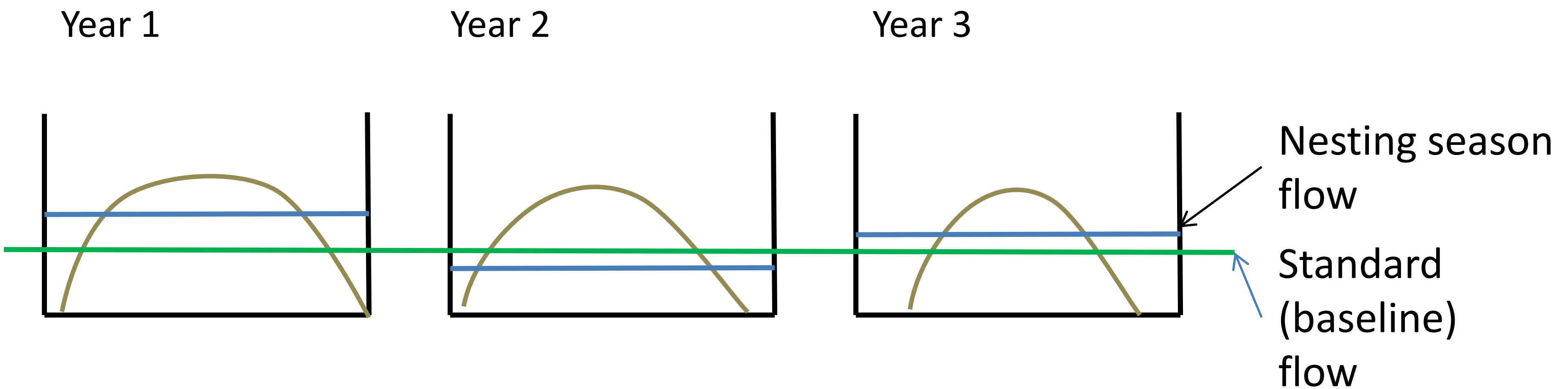
ERDC
Engineer Research and Development Center

- Based on the POR from 1930 – 2012
- Historical inflows with current depletions and evaporation
- Current reservoir operating criteria, except as dictated by a given scenario
- Mean Daily conditions (flow, stage, pool elev) available for each reservoir and at ten computation points

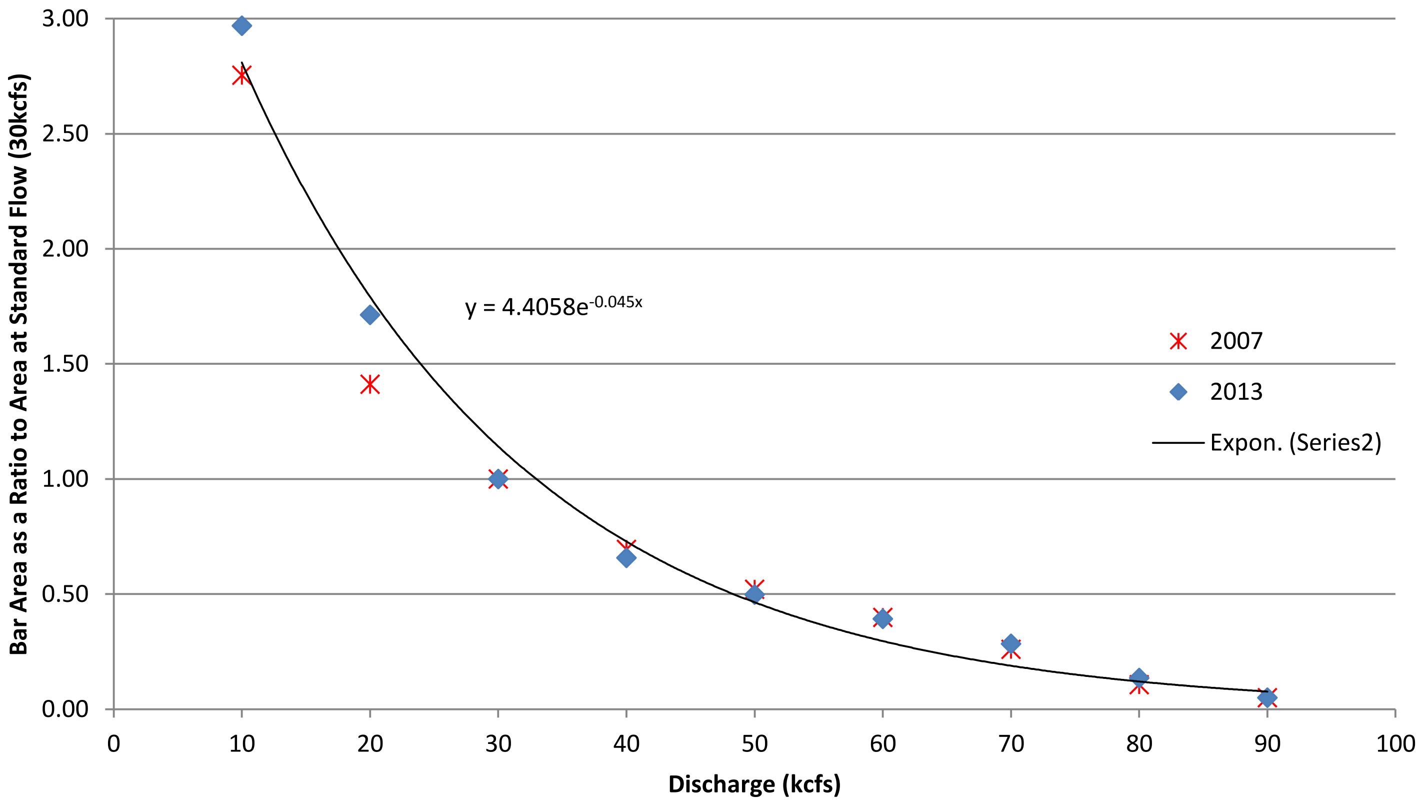
# Definition of ESH Metrics

Engineer Research and Development Center



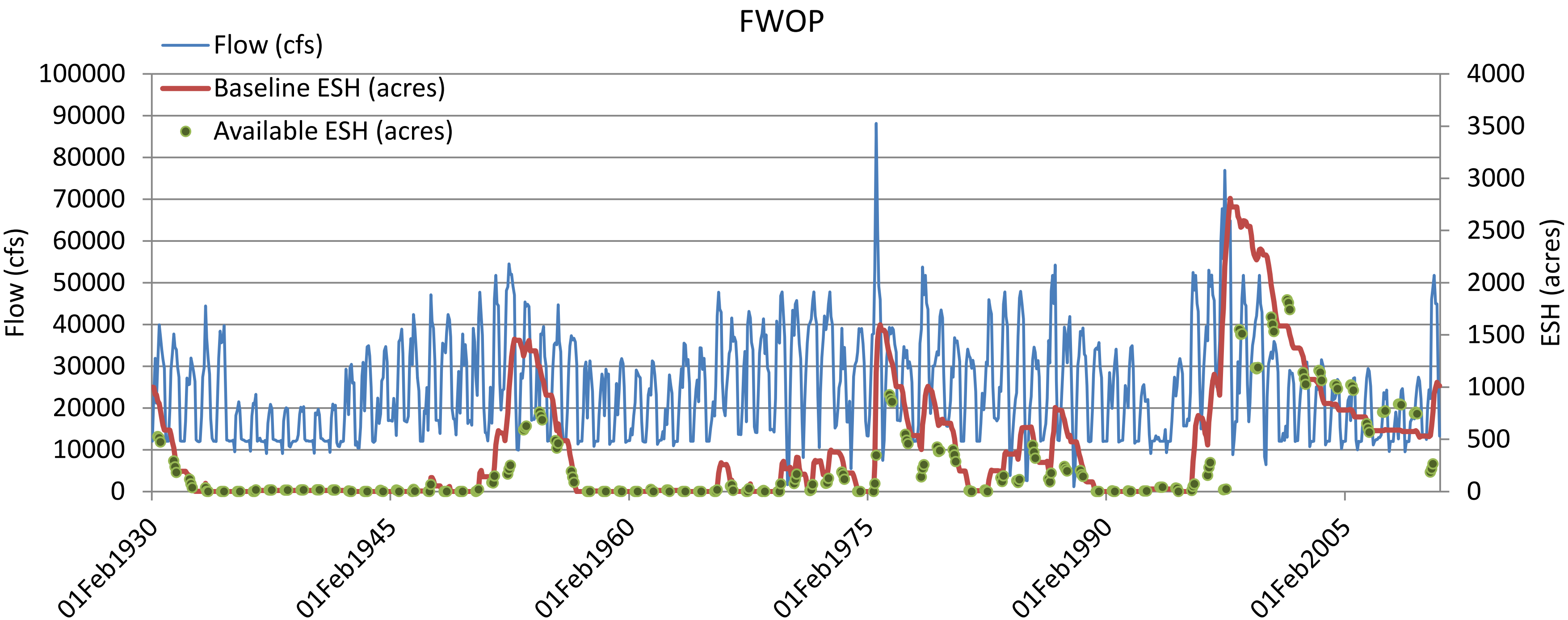



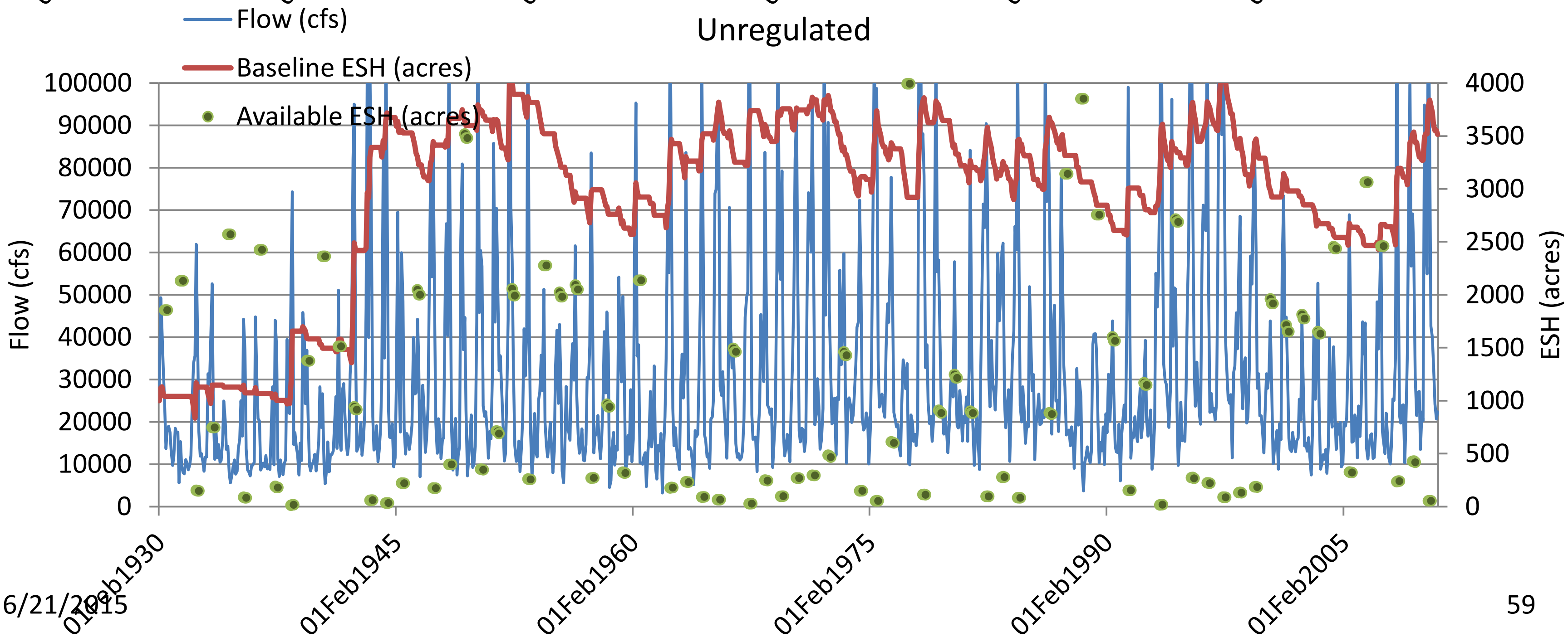
# Stage-Area Relation



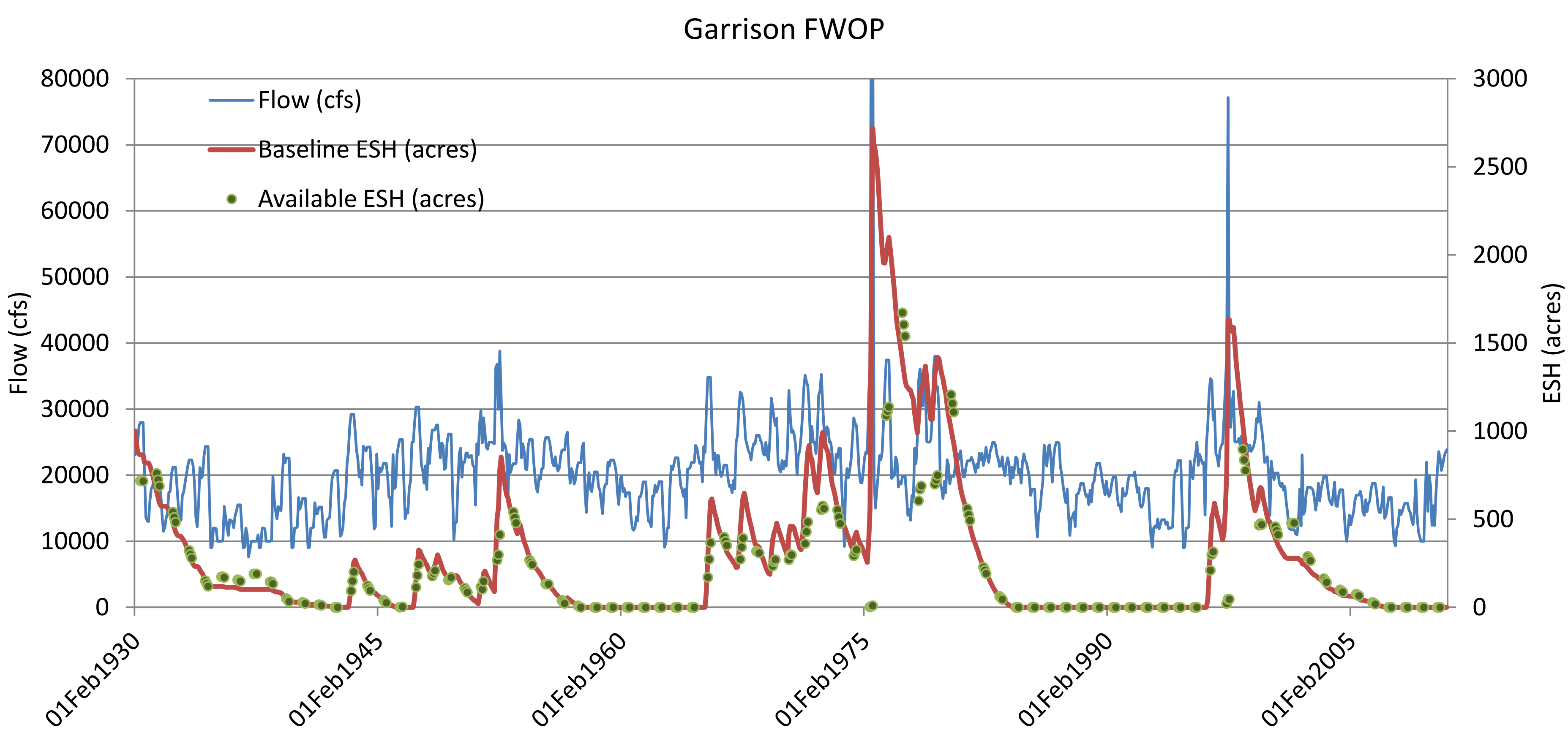

$$Y = 4.123e^{-0.045Q}$$

$$ESH_Q = Y * ESH_{base}$$


FWOP
Flow (cfs)
Baseline ESH (acres)
Available ESH (acres)
Flow (cfs)
ESH (acres)
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
4000
3500
3000
2500
2000
1500
1000
500
0
01Feb1930
01Feb1945
01Feb1960
01Feb1975
01Feb1990
01Feb2005


Unregulated
Flow (cfs)
Baseline ESH (acres)
Available ESH (acres)
Flow (cfs)
ESH (acres)
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
4000
3500
3000
2500
2000
1500
1000
500
0
01Feb1930
01Feb1945
01Feb1960
01Feb1975
01Feb1990
01Feb2005

# Garrison - Oahe



# Ft. Randall - LCL

Engineer Research and Development Center